



Technical Report 2018
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J. J. Beel, CAPT, USN
Commanding Officer

C. A. Keeney
Executive Director

ADMINISTRATIVE INFORMATION

This work described in this report was prepared for the Navy Environmental sustainability Development to Integration (NESDI) Project 424, with assessment of vapor intrusion with portable analytical systems is supported by the Environmental Security Technology Certification Program (ESTCP) under Project ER-201119 on "Use of On-Site GC/MS Analysis to Distinguish between Vapor Intrusion and Indoor Sources of VOCs." Dr. Tom McHugh is the principal investigator of this project, which includes collaboration from SSC Pacific.

This report was prepared by the Research and Applied Sciences Department (Code 70), SPAWAR Systems Center Pacific (SSC Pacific), San Diego, CA.

Released by
C. Katz, Head
Environmental Sciences Branch

Under authority of
M. J. Machniak, Head
Advanced Systems & Applied
Sciences Division

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Technical collaborators for the demonstration of the use of passive samplers include Mr. Todd McAlary, Ms. Hester Groenevelt, Mr. Todd Creamer, Mr. Paul Nicholson, Ms. Rachel Klinger and Mr. David Bertrand, of Geosyntec Consultants, Inc. (Geosyntec). Passive samplers were demonstrated in coordination with Environmental Security Technology Certification Program (ESTCP) Project ER-0830, “Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques,” Mr. Todd McAlary is the Principal Investigator (PI) of this project. Pressure control was demonstrated in collaboration with Dr. Thomas McHugh, Ms. Lila Beckley, and Ms. Danielle Bailey, of GSI Environmental Inc. (GSI). This demonstration was done in coordination with ESTCP Project ER-0707, “Protocol for Tier 2 and Evaluation of Vapor Intrusion at Corrective Action Sites.” Dr. Thomas McHugh is the PI of the project.

This effort benefited from the input from a broad range of people, including direct input from the Project Review Team (PRT) made up of remedial project managers (RPMs), users, and managers. Members of the PRT are Jennifer Corack, Navy Marine Corps Public Health Center (NMCPHC); William Corl, Naval Sea Systems Command (NAVSEA); Amy Hawkins, Naval Facilities Engineering Command Engineering Services Center (NAVFAC ESC); Ruth Owens, NAVFAC ESC; Kim Brown, NAVFAC Headquarters; Donna Caldwell, NAVFAC Atlantic; Kathleen Paulson, NAVFAC ESC; Melinda Trizinsky, NAVFAC Southwest; Dan Waddill, NAVFAC Atlantic; and Vera Wang, NMCPHC.

Demonstration of the pressure control included concurrent verification within the U.S. Environmental Protection Agency (EPA) Environmental Technology Verification (ETV) Program. The Verification Test Coordinator was Mr. Ian MacGregor, Battelle; Ms. Amy Dindal, Battelle, is Center Program Manager at the ETV’s Advanced Monitoring Systems (AMS). Mr. Jonathan Tucker, NAVFAC Atlantic, was the Quality Assurance Officer for the verification. Members of the technical panel for the U.S. EPA ETV for verification of pressure control are Donna Caldwell, NAVFAC Atlantic; D. Bart Chadwick, SSC Pacific; Jennifer Corack, NMCPHC; William Corl, NAVSEA Norfolk Naval Ship Yard; Helen Dawson, U.S. EPA; Dominic DiGiulio, U.S. EPA Office of Research and Development (ORD); Douglas Grosse, U.S. EPA/ORD Naval Risk Management Research Laboratory (NRMRL); Amy Hawkins, NAVFAC ESC; Michael Helbling, NAVFAC Headquarters; Michelle Henderson, U.S. EPA; Paul Johnson, Arizona State University; Thomas McHugh, GSI Environmental, Inc.; John McKernan, U.S. EPA ETV AMS; David Mikunas, Electronic Reporting Tool (ERT) - U.S. EPA Trace Atmospheric Gas Analyzer (TAGA); Ronald Mosley, U.S. EPA/ORD/NRMRL; Ruth Owens, NAVFAC ESC; Kathleen Paulson, NAVFAC ESC; Mathew Plate, U.S. EPA Region 9; Ignacio Rivera-Duarte, SSC Pacific; Brian Schumacher, U.S. EPA/ORD National Exposure Laboratory Environmental Sciences Division LV (NERL/ESD-LV); Henry Schuver, U.S. EPA; Melinda Trizinsky, NAVFAC Southwest; Dan Waddill, NAVFAC Atlantic; and Vera Wang, NMCPHC. Ms. Donna Caldwell, NAVFAC Atlantic, Mr. Ronald Mosley, U.S. EPA/ORD/NRMRL, and Mr. Brian Schumacher, U.S. EPA/ORD/NERL/ESD-LV, provided final comments for the U.S. EPA ETV Report.

EXECUTIVE SUMMARY

Vapor intrusion (VI) is a form of indoor air pollution caused by the migration of chemical vapors from contaminated soil and groundwater into buildings. This exposure pathway has attracted significant attention from regulatory agencies over the past decade in response to several well-publicized cases. Vapor intrusion assessments are performed during environmental restoration, base realignment and closure, and at underground tank storage sites. Currently, the Navy has spent more than \$10 million on these assessments and their associated remediation.

A survey of Navy remedial project managers at 97 sites found 25 bases where VI issues are being addressed. The known costs for addressing the issues at these bases ranged from \$15,000 to \$2 million per installation. Part of the reason for these high costs is that there are too many uncertainties involved with the current methods for VI assessment. These uncertainties stem from the unknown relationship between subsurface contaminants in water, soil, or soil gas to indoor air concentrations. The problem is exacerbated by the potential presence of sources of chemical vapors within and outside the building.

Currently, traditional assessments have relied primarily on modeling to predict indoor air exposure levels from subsurface concentrations. However, site-specific conditions limit the ability of these models to provide accurate predictions, generally leading to overly conservative assessments. Federal and state regulators are becoming resistant to VI modeling as a method to predict indoor air concentrations, and are moving towards recommending indoor vapor sampling for all sites. These facts point to the urgent need to adopt alternatives to VI modeling.

In response to the need for research and development on reducing costs and uncertainties associated with vapor intrusion, the Space and Naval Warfare Systems Center Pacific (SSC Pacific) in partnership with Naval Facilities Engineering Service Center (NFESC), Geosyntec, and Groundwater Services Inc. (GSI), began working on this project in 2008. The team has determined that the best potential for cost-effective reduction of the overall uncertainty is to develop an integrated strategy that combines direct measurement methods with forensic methods to partition background sources directly in indoor air. This is generally described as a “top-down” approach.

A project review team provided user input into the best approach to acknowledge vapor intrusion issues in Navy sites. Following directions from the project review team, a group of subject-matter experts was commended to identify existing best practices, knowledge, and data gaps, and future research in vapor intrusion assessment strategies. In 2009, the group released SSC Pacific Technical Report 1982 (SSC Pacific, 2009), which offers suggestions for research in the following three focus areas identified by a group of Navy end-users:

- Sub-surface sampling that minimizes intrusive sub-slab sampling
- Indoor air sampling methods that improve vapor intrusion exposure estimates
- Methods to differentiate between indoor and vapor intrusion sources

Regarding methods to differentiate between indoor and vapor intrusion sources, the team gathered feedback from the project review team. Three critical technologies were identified, including:

1. The use of building pressure control for differentiation between background and vapor intrusion
2. The use of quantitative passive samplers for measurement of long-term average indoor air concentrations more representative of health exposures
3. The use of portable analytical systems for the identification of indoor areas of greatest concern

Two of these technologies, passive samplers and building pressure control, were demonstrated as part of Navy Environmental Sustainability Development to Integration (NESDI) Project 424. The third technology, assessment of VI with portable analytical systems, is being supported by the Environmental Security Technology Certification Program (ESTCP) under Project ER-201119 on “Use of On-Site GC/MS Analysis to Distinguish between Vapor Intrusion and Indoor Sources of VOCs.” Dr. Tom McHugh is the principal investigator of this project, which includes collaboration from SSC Pacific.

This report includes findings and results from the demonstration of passive samplers and building pressure control in eight Department of Defense (DoD) sites. Due to the nature of the methods, as well as to programmatic factors, researchers were unable to demonstrate both methods at all of the sites, and some of the sites were only tested with one of the two methods. However, the experience and recommendations developed from these demonstrations is applicable to many other DoD and industrial sites in general. Navy site managers and the public can use this technical report to apply passive samplers and/or build pressure control supporting improved VI assessment by following methodology proved in this effort, which is available to the regulatory and scientific communities, as well as to the general user. The recommendations specifically provide direction on the collection of indoor air and soil gas samples supporting vapor intrusion assessment. This “top-down” approach should provide the appropriate information required to support “No Further Action” at sites eligible for such action. The potential for return on investment for this project is significant because it can provide a basis for continued research and provide cost-effective, accepted solutions to support effective vapor intrusion assessment.

Use of passive samplers for assessment of volatile organic compound (VOC) concentrations at a relevant regulatory level is supported by the demonstrations. While some parameters must be considered for the appropriate measurement of indoor air vapor concentration, these were evaluated and are described in this report. The report also provides a table of reference for selection of a single unit or a set of passive samplers for assessment of indoor vapor concentrations (Table 4). The table provides the deployment time required to achieve a reporting limit corresponding to a residential indoor air screening level of 1×10^{-6} incremental lifetime cancer risk, for solvent or thermal analysis, and for different types of adsorbents. Achieving this threshold level should allow for “No Further Actions” in those cases where VOC concentrations in indoor air are at a level lower than the threshold.

Based on the demonstration results of passive samplers, the authors of this report have reached the following conclusions:

- All of the passive samplers provided data that met the success criteria of measurements within $\pm 30\%$ for indoor air and/or $\pm 50\%$ for soil gas samples of VOC concentrations measured with conventional Summa™ canisters under some conditions. Exceptions were generally attributable to starvation or poor retention (explained further below).
- Poor retention causes a negative bias in the passive sampler concentration results compared with Summa™ canisters. This condition was observed in cases where the equivalent sample volume (sampler uptake rate multiplied by the exposure duration) was much larger than the safe sampling volume for a particular compound and adsorbent. The safe sampling volume is specific for each chemical and adsorbent. Where necessary, a stronger adsorbent may be selected to increase the safe sample volume and reduce the risk of poor retention.

- Starvation also causes a negative bias, and occurs in cases where the uptake rate is high relative to the face velocity of gas near the sampler. Starvation is exacerbated in subsurface (sub-slab and soil gas) sampling, where the face velocity is expected to be very low. Low-uptake-rate versions of several passive samplers were developed during the conduct of this research, and tended to minimize this effect.
- Positive biases were less common than negative biases, and attributed either to blank contamination (e.g., perchloroethylene (PCE) for the SPAWAR Knowledge Center (SKC) at Old Town Campus, Building 3), or to uncertainty in the uptake rates.
- Passive samplers provided reproducible results throughout the demonstrations, even in the cases where there was either positive or negative bias. This consistency in measuring VOC concentrations allows for improvements in accuracy using a selected number of simultaneous duplicate samples using conventional SummaTM canisters with minimal implication on cost.
- Selection of the most appropriate sampler for a particular application depends on the target compounds (not all sampler types have measured uptake rates for all chemicals), target concentrations (some samplers have better sensitivity than others), ambient gas flow velocities (low-uptake-rate samplers are preferable in low velocity environments), desired exposure duration (weaker sorbents suffer from poor retention over longer deployment intervals), and convenience (drilling a 2-inch-diameter hole in a concrete slab is much more work than drilling a ½-inch-diameter hole, and some exposure durations required to meet screening levels may be longer than desired). With the various combinations of each sampler type (high- and low-uptake versions, and various types of adsorbents), the selection process involves several considerations, and should be reviewed carefully by an experienced professional.

Use of the Pressure Control Investigation Procedure is validated by the results for the demonstration in six DoD buildings. This demonstration was done concurrently with verification of the methodology by the United States Environmental Protection Agency (U.S. EPA) Environmental Technology Verification (ETV) Program, with results published on its web site (<http://www.epa.gov/nrmrl/std/etv/vt-ams.html#sctvi>). An article describing the method and results was published in the *Environmental Science and Technology* journal (McHugh et al., 2012).

The two main findings from the demonstration of building pressure control are that it allows for differentiation between indoor and sub-slab sources of VOCs, and provides information on the worst-case scenario for positive vapor intrusion (McHugh et al., 2012). These are two situations that could protract the assessment of vapor intrusion. Indoor sources can produce VOC concentrations above regulatory thresholds, and are difficult to identify. The presence of indoor VOC sources could produce false positive VI results, and identification and isolation of indoor sources is critical for correct assessment of vapor intrusion. Temporal variation on vapor VI has been observed, and reliable documentation on the case when vapor intrusion is active is required to select appropriate control actions. Manipulation of building pressure control induces those conditions of active vapor intrusion, allowing for reliable and expeditious assessment of this condition.

The authors of this report reached the following conclusions from the results of the demonstration of the Building Pressure Control Investigation Procedure:

- Statistical analysis (i.e., analysis of variance [ANOVA]; $p = 0.03$) of the change of indoor air VOC concentration between controlled negative and positive pressure conditions shows that control of building pressure provides the ability to distinguish between VOCs originating from subsurface sources, and VOCs originating from above-ground sources.

- For the six demonstration buildings, the change in VOC concentration in indoor air between the controlled negative pressure condition and the controlled positive pressure condition matched the predicted change for subsurface VOCs (i.e., decrease in concentration) for 17 of 19 cases and matched the predicted change for above-ground VOCs (i.e., no change or change matching the change in ambient concentrations) in 16 of 20 cases.
- The changes in VOC concentration in sub-slab samples did not generally match the predicted change of increasing concentration under a positive pressure condition.
- Correlation between measured foundation permeability and the magnitude of vapor intrusion in the six demonstration buildings was unclear.
- Implementation of the investigation procedure twice in each of two demonstration buildings showed that the procedure yields reproducible results.
- The Pressure Control Investigation Procedure can be used to control temporal variability in buildings with episodic vapor intrusion (e.g., Hill Air Force Base Arizona State University Research House).
- The investigation procedure can accurately identify vapor intrusion in buildings where the standard lines of evidence approach would incorrectly suggest an indoor source (e.g., Moffett Field Building 107).

The results from these demonstrations attest to the capability of passive samplers and building pressure control for assessment of vapor intrusion. These demonstrations provided information of the use of passive samplers for long-term quantification of VOCs. They also provided the knowledge for correct use of passive samplers under a suite of conditions. Similarly, it was demonstrated that building pressure control could assess indoor sources, VI, and the worst-case scenario for positive vapor intrusion. Applying these top-down approaches should streamline initial, and ongoing, assessment of VI, and should provide the evidence required for “No Further Action” when that condition is endorsed.

CONTENTS

EXECUTIVE SUMMARY	iii
ACCRONYMS AND ABBREVIATIONS	xv
1. INTRODUCTION	1
1.1 BACKGROUND	1
1.2 OBJECTIVE OF THE DEMONSTRATION	3
1.3 REGULATORY DRIVERS	4
2. TECHNOLOGY DESCRIPTION	5
2.1 PASSIVE SAMPLERS	5
2.1.1 Passive Samplers—Technology Description	5
2.1.2 Passive Samplers—Physical Description	6
2.1.3 Advantages of Passive Samplers	11
2.1.4 Limitations of Passive Samplers	12
2.2 BUILDING PRESSURE CONTROL	13
2.2.1 Building Pressure Control – Technology Description	13
2.2.2 Advantages of Building Pressure Control	14
2.2.3 Limitations of Building Pressure Control	14
3. DEMONSTRATION DESIGN	15
3.1 PERFORMANCE OBJECTIVES	15
3.2 PASSIVE SAMPLERS – DEMONSTRATION DESIGN	15
3.2.1 Passive Samplers: Quantification Accuracy in Soil Gas, Indoor and Outdoor Air	15
3.3 PRESSURE CONTROL – DEMONSTRATION DESIGN	15
3.3.1 Building Pressure Control: Collection of Data Representative of Site Conditions	15
3.3.2 Validation of Building Pressure Control Investigation Procedure	18
3.3.3 Development of Building Pressure Control Investigation Procedure	18
4. SITE SELECTION	19
4.1 SITE DESCRIPTIONS	19
4.1.1 Hill Air Force Base	19
4.1.2 Marine Corps Air Station Cherry Point	19
4.1.3 Moffett Field Naval Air Station	22
4.1.4 Naval Air Station Jacksonville	23
4.1.5 Marine Corps Recruit Depot Parris Island	24
4.1.6 SPAWAR Systems Center Pacific Old Town Campus	25
4.1.7 Tinker Air Force Base	25
4.1.8 Travis Air Force Base	25
5. TEST DESIGN	27
5.1 PASSIVE SAMPLERS – TEST DESIGN	27
5.1.1 Passive Samplers Methods	27
5.1.2 Laboratory Analysis	36
5.2 BUILDING PRESSURE CONTROL – TEST DESIGN	37
5.2.1 Design and Layout of Technology Components	38
6. RESULTS	43
6.1 PASSIVE SAMPLERS - RESULTS	43
6.1.1 Building 3 at SSC Pacific Old Town Campus (OTC3)	43

6.1.2 MCAS 137	53
6.1.3 Naval Air Station Jacksonville	54
6.1.4 Overall Summary Results for Each Passive Sampler Type	69
6.1.5 Considerations for Sampler Selection	70
6.2 BUILDING PRESSURE CONTROL - RESULTS	75
6.2.1 Air Exchange Rate	75
6.2.2 Chemical Concentrations	77
6.2.3 Cross-Foundation Pressure Gradients.....	77
6.2.4 Collection of data representative of site conditions	77
6.2.5 Evaluation of Data Quality Performance Objective	82
6.3 VALIDATION OF PRESSURE CONTROL INVESTIGATION PROCEDURE.....	83
6.3.1 Analysis of Variance.....	84
6.3.2 Site-by-Site Analysis of Results	85
6.3.3 Other Analysis of Demonstration Results	89
6.3.4 Summary of Validation of Pressure Control Investigation Procedure.	91
6.4 PRESSURE CONTROL INVESTIGATION PROCEDURE	92
6.4.1 Overview of Pressure Control Investigation Procedure	92
6.4.2 Pressure Control Investigation Procedure	93
7. COST ASSESSMENT	97
7.1 COSTS ASSOCIATED WITH PASSIVE SAMPLERS	97
7.1.1 Cost Scenario 1 for Passive Samplers.....	97
7.1.2 Cost Scenario 2 for Passive Samplers.....	101
7.2 COSTS ASSOCIATED WITH BUILDING PRESSURE CONTROL	101
7.2.1 Cost Drivers	101
7.2.2 Cost Analysis	101
7.2.3 Operational Implementation Costs for the Building Pressure Control Investigation Procedure.....	101
9. REFERENCES	103

Figures

1. SKC Ultra Sampler (left), and high and low uptake caps (right)	7
2. Radiello® sampler and high-uptake white and low-uptake yellow bodies	8
3. 3M OVM 3500 passive sampler showing solid plastic cap used to replace porous plastic sheet after sampling is complete.....	8
4. Waterloo membrane sampler showing two cross-sectional setups, and close-up of membrane and adsorbent.....	9
5. ATD sampler set for sub-slab sampling, and regular and low-uptake-rate caps	10
6. Setup of a pair of Summa™ canisters connected to a single intake valve used for demonstration. For size comparison, a 3M OVM 3500 passive sampler is on the top-right corner.....	12
7. Conceptual illustration of building pressure control for building-specific assessment of vapor intrusion.....	14
8. Front view of ASU Vapor Intrusion Research House in Layton, UT.....	20
9. Diagram of ASU Vapor Intrusion Research House in Layton, UT, with locations of sampling points for pressure control demonstration	21
10. Diagram of MCAS 137 with sampling locations	21
11. Diagram of MCAS 137 with sampling locations	22
12. Front view of Building 107 at Moffett Field Naval Air Station	22

13. Diagram of Building 107 at Moffett Field Naval Air Station with sampling locations	23
14. Diagram of Building 103 in Naval Air Station Jacksonville, Florida, with sampling locations, and sub-slab and indoor air data on the left reported by GSI Inc. (2009)	24
15. Diagram of new drycleaning facility at Marine Corps Recruit Depot (MCRD) Parris Island, SC, with sampling locations	24
16. Diagram showing SSC-Pac OTC3 vapor intrusion study area (left) and sampling point locations (right).....	25
17. Diagram of Building 200 at Tinker AFB, with sampling locations.....	26
18. Diagram of Building 828 at Travis AFB with sampling locations	26
19. Example of sampling array for demonstration of passive samplers for indoor air VOC assessment (OTC3).....	28
20. Schematic of sub-slab probe setting	30
21. Sub-slab probe array (OTC3)	31
22. Lung Box used to purge sub-slab probes prior to passive sampler deployment	32
23. Deployment of fully passive ATD tube sample, showing wire basket used to prevent contact with soil at the bottom of the cored hole, steel wire tether for retrieval and rubber stopper wrapped in aluminum foil used as a temporary cap.....	33
24. Passive soil gas probe showing aluminum stilts used to suspend the pipe above the bottom of the augured hole and the plastic sleeve that was filled with tamped sand to seal the borehole annulus, both of which are secured with a stainless steel ring clamp.....	34
25. Cap of passive soil gas probe, with fittings for purging line (extends to just below cap) and Summa™ canister sampling line (extends through 1/8-inch stainless steel tubing to bottom of PVC pipe).....	34
26. Collection of soil gas samples with Summa™ canisters	35
27. Radiello®, WMS, and ATD samplers wrapped to protect them from contact with soil	36
28. Example of sub-slab sample port and sample train, and construction specifications for sub-slab sampling points	38
29. Set-up for cross-foundation measurement with pressure transducer. Note that reference port is located to the right-hand side of the sub-slab connection on the Omniguard transducer	39
30. SF6 tracer gas release system	40
31. Collection of indoor and sub-slab samples for demonstration of pressure control.....	41
32. Correlation between passive samplers and Summa™ canisters for TCE ($\mu\text{g m}^{-3}$) in indoor air at OTC3.....	45
33. Correlation among passive samplers and Summa™ canisters for cDCE ($\mu\text{g m}^{-3}$) in indoor air from OTC3.....	46
34. Stacked bar representation of TCE concentration ($\mu\text{g m}^{-3}$) in indoor air at OTC3. Bars to the left side (labeled IA-1, IA-2, and IA-3) are the average of the three samples collected at that location, and average bars to the right are the average indoor air concentrations at the three locations	46
35. Correlation between VOC concentrations ($\mu\text{g m}^{-3}$) measured with passive samplers and Summa™ canisters in indoor air from OTC3	49
36. Sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-2 in OTC3, measured after 2 hours of fully passive sampling	49
37. Sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-5 in OTC3, measured after 15 hours of fully passive sampling (empty bars represent non-detect results)	50
38. Semi-passive sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-3 in OTC3. These were sampled by intermittent purging with a PID unit. The data is not corrected for spatial variability in PID readings	50
39. Starvation factor versus uptake rate for fully passive sub-slab samples from OTC3.....	51

40. Comparison between passive sampler sampling approach (passive and semi-passive) to conventional Summa™ canister.....	52
41. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. Two plots are presented for each passive sampler to show both the complete range of concentrations (log-log plot) and a closed up of the lowest concentration range. SKC Ultra a, b; Radiello® c, d; ATD e, f; 3M OVM g, h; WMS i, j	62
42. Correlation between soil gas concentrations measured with passive samplers and conventional Summa™ canisters samplers	67
43. Correlation between passive sub-slab samples and Summa™ canister samples at NAS JAX.	68
44. Comparison between all the accepted measurements for the three demonstration sites with each passive sampler, versus conventional Summa™ canister	73
45 . Predicted change in VOC concentration between negative building pressure and positive building pressure sampling events, under permeable foundation conditions (e.g., the indoor air concentration of VOCs originating from a subsurface source are expected to be lower under positive building pressure conditions compared to negative building pressure conditions)	84
46. Effect of building pressure control on concentration of radon in indoor air	89
47. Comparison of concentration results over two rounds of testing	90
48. Conceptual illustration of building pressure control for the building-specific evaluation of vapor intrusion.....	94
49. Pressure control method field schedule: routine application.....	95

Tables

1. Performance objectives	16
2. Demonstration sites	20
3. Number of passive samplers used in each demonstration, as well as type of sorbent and laboratory desorption method	29
4. Summary of evaluation sampling program	37
5. Field demonstration schedule pressure control	37
6. Analytical methods used for sample analysis for pressure control	41
7. Analytical results for trip blanks from the OTC3 demonstration effort.....	45
8. Analytical results for indoor air (IA) and outdoor air (OA) from OTC3.....	47
9. Analytical results for sub-slab (SS) measurements from OTC3.....	48
10. Correction factors for passive samplers used at location SS-3	51
11. Analytical results for indoor air (IA) and outdoor air (OA) at MCAS 137	55
12. Analytical results for soil gas and sub-slab VOCs sampled with conventional Summa™ canisters at NAS JAX.	63
13. Analytical results for passive soil gas samples at NAS JAX	64
14. Analytical results for passive sub-slab samples at NAS JAX.....	65
15. Statistics for the correlation between each passive sampler and conventional Summa™ canister VOC measurements for the three demonstration sites	70

16. Exposure time for selection of appropriate single-unit or set of passive samplers for indoor air screening. The reference concentration is the residential indoor air screening level corresponding to a 1×10^{-6} incremental lifetime cancer risk. The exposure duration required for each passive sampler with either solvent or thermal analysis to achieve a reporting limit equal to the screening level is provided	74
17. Summary of pressure control testing program at each demonstration site	75
18. Building air exchange rates (day-1)	76
19. Predicted* versus measured chemical concentrations under positive pressure conditions in Travis AFB Building 828	76
20. Chemical concentrations in demonstration buildings	78
21. Average cross-building envelope and cross-foundation pressure gradients during demonstrations	81
22. Summary of field duplicate precision	82
23. Summary of data evaluation results	83
24. Observed change in concentration between building test conditions	87
25. Pressure control method sampling program: routine application	95
26. Use of radon concentration data to verify method performance	95
27. Costs associated with conventional active Summa™ canister and passive samplers for Cost Scenario 1.	95
28. Costs associated with conventional active Summa™ canister and passive samplers for Cost Scenario 2	96
29. Costs associated with conventional active Summa™ canister and passive samplers for Cost Scenario 3	97
30. Costs associated with conventional active Summa™ canister and passive samplers for Cost Scenario 4	99

ACRONYMS AND ABBREVIATIONS

11DCA	1,1-dichloroethane
11DCE	1,1-dichloroethene
111TCA	1,1,1-trichloroethane
12DCA	1,2-dichloroethane
112TCA	1,1,2-trichloroethane
$\mu\text{g m}^{-3}$	Micrograms per cubic meter
AFB	Air Force Base
AMS	Advanced Monitoring Systems Center
ASU	Arizona State University
ATD	Automatic Thermal Desorption
ATD/GC/MS&FID	ATD tube analysis by Gas Chromatography/Mass Spectrometry or flame ionization detection
BTEX	Benzene, Toluene, Ethylbenzene, and Xylene
CAS	Columbia Analytical Services
cDCE	cis-1,2-dichloroethene
DoD	Department of Defense
DON	Department of the Navy
ESTCP	Environmental Security Technology Certification Program
ETV	Environmental Technology Verification Program
FID	Flame Ionization Detection
GC	Gas Chromatography
GC/MS	Gas Chromatography/Mass Spectrometry
ITRC	Interstate Technology and Regulatory Council
LCS/LCSD	Laboratory Control Sample/Laboratory Control Sample Duplicate
LTPRI	Linear Temperature Programmed Retention Index
MCAS	Marine Corps Air Station
MCAS 137	Marine Corps Air Station Cherry Point Building 137, North Carolina
MCRD	Marine Corps Recruit Depot
MS/MSD	Matrix Spike/Matrix Spike Duplicate
NAS	Naval Air Station
NAS JAX	Naval Air Station Jacksonville, Florida
NESDI	Navy Environmental Sustainability Development to Integration program
NFESC	Naval Facilities Engineering Service Center
NJDEP	New Jersey Department of Environmental Protection
OTC3	SSC Pacific Old Town (Campus) Building 3, San Diego, California
OU	Operable Unit
OSWER	Office of Solid Waste and Emergency Response
Pa	Pascal
ppmv	Parts per million by volume
PCE	Tetrachloroethene or perchloroethene
PID	Photoionization Detector
PDMS	Polydimethylsiloxane
QA/QC	Quality Assurance/Quality Control
RPD	Relative percent Difference

RPM	Remedial Project Manager(s)
SSV	Safe Sampling Volume
SIM	Selected Ion Monitoring
SERDP	Strategic Environmental Research and Development Program
SF ₆	Sulfur Hexafluoride
SSC Pacific	Space and Naval Warfare (SPAWAR) Systems Center Pacific
tDCE	trans-1,2-dichloroethene
TCE	Trichloroethene
U.S. EPA	United States Environmental Protection Agency
VC	Vinyl chloride
VI	Vapor Intrusion
VOC	Volatile Organic Compound
WMS	Waterloo Membrane Sampler
WIOU	Western Industrial Operable Unit

1. INTRODUCTION

1.1 BACKGROUND

Since 2000, regulators and the regulated community have become increasingly concerned about the potential for exposure to volatile organic compounds (VOCs) through vapor intrusion (VI) to indoor air at sites with contaminated soil or groundwater. Detailed investigations at a limited number of corrective action sites have documented elevated levels of chlorinated VOCs in houses located above contaminated groundwater (Tillman and Weaver, 2005; DiGiulio et al., 2006). Because the Department of Defense (DoD) is responsible for environmental compliance at thousands of sites contaminated with VOCs, assessment of the extent of VI, and of the potential health concerns associated with VI, are frequently enforced. For sites where VI is a potential concern, long-term monitoring will also presumably be needed, which will incur significant costs for responsible parties. In response to the need for VI assessment, the United States Environmental Protection Agency (U.S. EPA) Office of Solid Waste and Emergency Response (U.S. EPA, 2002), about 27 state regulatory agencies, and the Interstate Technology and Regulatory Council (ITRC, 2006) have issued guidance specifying screening and field investigation procedures for identifying VI impacts at corrective action sites. Although the specific recommended investigation procedures vary significantly between guidance documents, most of these documents use a step-wise evaluation process that includes preliminary screening followed by field investigation, if needed.

Of the available regulatory guidance on VI, the U.S. EPA guidance (U.S. EPA, 2002) is currently the most widely applied. This guidance document has been formally adopted by some states (e.g., Ohio) and is also widely used in states that have not issued their own guidance documents. The U.S. EPA Vapor Intrusion Guidance recommends the following step-wise evaluation approach:

Presence of Volatile Chemicals: Vapor intrusion is a potential concern at sites with soil or groundwater impacted by volatile chemicals. Corrective action sites without volatile chemicals (typically defined by vapor pressure and/or Henry's Law constant) require no further evaluation for VI. Example volatility criteria are as follows:

- U.S. EPA (2002): Volatile chemicals are defined based on Henry's Law Constant as $>1 \times 10^{-5} \text{ atm}\cdot\text{m}^3 \text{ mol}^{-1}$
- New Jersey Department of Environmental Protection (NJDEP), 2006: Volatile chemicals are defined based on Henry's Law Constant as $>1 \times 10^{-5} \text{ atm}\cdot\text{m}^3 \text{ mol}^{-1}$ and a vapor pressure $>1 \text{ mm Hg}$

Pathway Screening Criteria: For sites with volatile chemicals in soil or groundwater, most regulatory guidance provides conservative screening criteria for preliminary evaluation of the VI pathway. Screening criteria are typically provided for groundwater and soil gas, and less commonly for soil. These criteria are typically used to evaluate the likelihood of whether VOCs are migrating away from a source area at concentrations that could cause a VI impact. Although exceedances of these criteria do not indicate that a VI impact has occurred or will occur, additional investigation of VI is required if the maximum VOC concentration is greater than the screening value within a defined distance (typically 100 feet) of a VI receptor (i.e., a current or future building). For some common constituents of concern (COCs), the U.S. EPA screening criteria for groundwater are equal to drinking water standards, and would have been lower had there not been a policy decision to truncate them at the maximum contaminant level. In addition, some soil gas screening criteria are less than or equal to typical analytical detection limits. As a result, few corrective action sites are screened out of further evaluation using these criteria.

Building-specific Evaluation: For sites with volatile chemicals present at concentrations above the screening criteria, most guidance documents require a field investigation to determine the presence or absence of VI impacts to nearby buildings (commonly defined as within 100 feet of VOC impacts). When conducting a site-specific field investigation, the U.S. EPA guidance recommends collection of below-foundation (i.e., sub-slab) gas samples followed by simultaneous below-foundation and indoor air sampling, if needed. The U.S. EPA guidance raises a number of data quality issues to be addressed as part of the field investigation, including indoor sources of VOCs (background), spatial variability, temporal variability, and sample collection and analytical variability. However, the guidance document does not provide a clear recommendation on the amount of data needed to account for these sources of variability and to make a definitive determination of the presence or absence of a VI impact. In the absence of clear guidance on the scope of the field investigation, the investigation approaches adopted by individual investigators have varied widely. As a result, disagreements may arise between parties involved at a site regarding the adequacy of a field investigation at a specific building.

Currently, the most common method for collection and analysis of indoor air, sub-slab, or soil vapor samples consists of drawing air or soil gas into an evacuated, passivated stainless steel container through a flow controller (i.e., Summa[™] canister) followed by shipment to a laboratory for analysis by U.S. EPA Method TO-15 (U.S. EPA, 1999a). The cost of analysis is relatively high because it includes canister rental, canister cleaning and certification, and flow controller rental in addition to the cost of analysis. Shipping costs are also relatively high because of the large size of the canisters. Sampling protocols for canisters are also relatively complicated, and operator errors may therefore cause data bias and variability.

Although most state vapor intrusion guidance documents use a step-wise investigation approach similar to the U.S. EPA guidance, most guidance documents use very low screening criteria for the preliminary evaluation. Some states (e.g., New York) do not allow screening based on subsurface VOC concentrations, but instead require indoor air testing at all field investigation sites (NYDOH, 2006). In addition, the U.S. EPA has indicated that revised VI guidance due in 2012 is unlikely to allow screening of the VI pathway based solely on soil gas concentration results (U.S. EPA, 2010). As a result, field investigations of the VI pathway are required at a majority of sites with subsurface volatile chemical impacts, and this will likely remain the case in future.

In response to the need for future research and development on reducing high costs and uncertainties of VI assessment strategies (Department of the Navy, DON, 2009), the Navy Environmental Sustainability Development to Integration (NESDI) program supported Project 424, “Improved Assessment Strategies for Vapor Intrusion.” The project included an overview by a team of subject-matter experts on current best practices, opinions on the current state of knowledge and data gaps, and suggestions for research directions for the following three Navy-identified VI focus areas (SSC Pacific, 2009):

- Subsurface sampling that minimizes intrusive sub-slab sampling
- Indoor air sampling methods to improve vapor intrusion exposure estimates
- Methods to differentiate between indoor and vapor intrusion sources

Three critical technologies were identified for differentiation between indoor and VI sources, with the input from a project review team. These technologies are:

1. Building pressure control for differentiation between background and vapor intrusion

2. Quantitative passive samplers for measurement of long-term mean indoor air concentrations better representative of health exposures
3. Portable analytical systems for the identification of indoor areas of greatest concern

Two of these technologies, passive samplers and building pressure control, were demonstrated as part of NESDI Project 424, in coordination with Environmental Security Technology Certification Program (ESTCP) Projects ER-0830 and ER-0707; the results of those demonstrations are presented in this report. The third technology, assessment of VI with portable analytical systems, is under support by ESTCP under project ER-201119 on “Use of On-Site GC/MS Analysis to Distinguish between Vapor Intrusion and Indoor Sources of VOCs.” Dr. Thomas McHugh, GSI Environmental Inc. (GSI) is the principal investigator of this project.

Demonstration of passive samplers was done in collaboration with Todd McAlary, Hester Groenevelt, Todd Creamer, Paul Nicholson, Rachel Klinger, and David Bertrand of Geosyntec Consultants, Inc. (Geosyntec). The demonstration was completed in coordination with ESTCP Project ER-0830, “Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques.” The focus of the demonstration was a head-to-head performance testing to demonstrate capabilities and limitations of multiple alternative designs to support regulatory acceptance. Collaboration also included testing of passive samplers at Navy sites, besides those already selected as part of Project ER-0830.

Building pressure control was demonstrated in collaboration with Dr. Thomas McHugh, Lila Beckley, and Danielle Bailey, GSI, in coordination with ESTCP Project ER-0707, “Protocol for Tier 2 and Evaluation of Vapor Intrusion at Corrective Action Sites” (McHugh, Beckley, and Bailey, 2012a). Building pressure control has been shown, in a very limited number of cases, to provide a very clear indication of VI and resolution of background contributions, but more work is required to develop a protocol accepted by regulatory agencies. For NESDI Project 424, testing of the pressure control technique was conducted under the auspices of U.S. EPA with verification by its Environmental Technology Verification Program (ETV, www.epa.gov/etv), and the Advanced Monitoring Systems Center (AMS) and Battelle (administrator of AMS). The ETV Program’s AMS Center conducts third-party performance testing of commercially available technologies that detect or monitor natural species or contaminants in air, water, and soil. The purpose of ETV is to provide objective and quality-assured performance data on environmental technologies, so that users, developers, regulators, and consultants can make informed decisions about purchasing and applying these technologies. The purpose of pursuing verification under the ETV Program is to provide third-party review of building pressure control, and increase regulatory acceptance as a validated VI assessment method. The verification report is available at the U.S. EPA ETV website at: <http://www.epa.gov/nrmrl/std/etv/vt-ams.html#sctvi>.

1.2 OBJECTIVE OF THE DEMONSTRATION

The general objective of NESDI Project 424 was to identify, evaluate, select and demonstrate promising field methodologies to optimize the assessment of the VI pathway at Navy sites. To accomplish this objective, Navy-critical areas had to be identified for optimization of VI assessment. The next task was to select technologies to reduce uncertainty associated with field assessment of attenuation, exposure levels, and background sources. Another task was to demonstrate/validate improved field assessment methodologies that provide cost-effective, quantitative interrogation of the VI pathway.

NESDI Project 424 had two final technical objectives. One was to demonstrate passive samplers for measurement of indoor VOC concentrations that represent the integration of exposure concentrations throughout the sampling period. The second technical objective was to develop and validate a simple procedure for using pressure control to assess VI in individual buildings. These objectives are the focus of this document.

1.3 REGULATORY DRIVERS

At a limited number of sites in the U.S., migration of VOCs from affected groundwater via vapor phase diffusion has impacted indoor air quality in overlying structures, posing a potentially significant, yet previously unrecognized human health concern for such properties. To address this concern, the U.S. EPA has issued the “Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils” (U.S. EPA, 2002), providing conservative screening criteria for various VOCs in groundwater. These conservative screening values eliminate few sites and, as a result, most sites with VOCs in groundwater require field investigation of the vapor intrusion pathway. The high level of conservatism in the U.S. EPA and state guidance reflects the current limitations of our understanding of the physical and chemical processes that contribute to the attenuation of vapors along the VI pathway. Development of a validated site- and building-specific (i.e., Tier 3) VI screening procedure will serve to reduce the number of sites where detailed field investigations are required to evaluate the VI pathway and will improve the efficiency of the site-specific field investigation, when required.

2. TECHNOLOGY DESCRIPTION

To assess vapor intrusion, two technologies, passive samplers and building pressure control, were demonstrated in this effort. Concentrations of VOCs measured with a suite of five commercially available passive samplers and conventional canisters were compared under two different settings. Building pressure control was also demonstrated in two separate settings, with concurrent verification by a third party as part of the U.S. EPA ETV Program. These two technologies are described in this section.

2.1 PASSIVE SAMPLERS

2.1.1 Passive Samplers – Technology Description

Quantitative passive samplers have been used for occupational hygiene monitoring for decades; however, their application to monitoring the very low concentrations typical of indoor and outdoor air in residential or normal commercial buildings is less extensively tested (Górecki and Namiesnik, 2002; Seethapathy et al., 2008). Five different types of passive diffusive sampling devices were compared; these are automatic thermal desorption (ATD) tubes, 3M OVM 3500, SKC Ultra, Waterloo Membrane Sampler (WMS), and Radiello® samplers.

Despite differences in their design, the basic principles of operation for all five passive samplers tested are similar. Each device is supplied by the laboratory certified clean and sealed in air-tight packing. The sampler is exposed to the air being investigated for a measured amount of time (t), during which VOCs diffuse or permeate into the device from the surrounding gas or atmosphere and a certain mass (M) of VOCs will be trapped on the adsorptive media within the device. The device is re-packed in an air-tight container and returned to the laboratory, where the mass adsorbed is quantified. Once the adsorbed mass has been quantified, the time-weighted average (TWA) concentration of a particular analyte in the sampled medium can be calculated using the following equation:

$$C_0 = \frac{M}{UR t} ,$$

where

C_0 TWA concentration in the sampled air ($\mu\text{g m}^{-3}$)

M mass of analyte on the sorbent (picograms, pg)

UR uptake rate (mL min^{-1})

t sampling time (min)

(Note: two offsetting conversion factors are from pg to μg and from mL to m^3)

In practice, adsorbed mass and exposure duration are both measured very accurately; therefore, the uptake rate is the key factor controlling the accuracy of the concentration measurement. The passive diffusive samplers included in this study are all designed to quantify the uptake rate, which distinguishes these devices from semi-quantitative passive samplers (e.g., Gore-Sorbers™, Beacon B-Sure™, EMFLUX Cartridges™, Petrex tubes™, and similar devices). The geometry of each of the candidate samplers is controlled to allow exposure over a measured cross-sectional area and diffusion or permeation through a medium where the diffusion coefficient or permeation constant for the chemicals of interest is known. This is necessary for the conversion of the mass measured on the adsorptive media to a TWA concentration at the face of the sampler. Concentrations are needed to compare to risk-based target concentrations for assessment of human health risks via VI.

Several samplers have more than one configuration option. Some of the samplers offer models with different uptake rates to either enhance sensitivity or avoid starvation. High uptake rates allow lower reporting limits to be achieved faster, which can be an advantage in some instances. Lower uptake rates reduce the risk of the “starvation effect,” which occurs when the sampler draws chemicals from its surroundings faster than they are replenished, which reduces the local concentrations and causes a negative bias in the results. For soil gas sampling, in particular, starvation is a concern because ambient flow rates for gas in soil are lower than flow rates in indoor or outdoor air.

Some samplers allow laboratory analysis to be performed using either thermal desorption or a solvent extraction method. Analysis by thermal desorption is typically performed using a method such as U.S. EPA Method TO-17 (U.S. EPA, 1999b), which provides very good sensitivity, as all of the mass adsorbed is injected into the gas chromatograph (GC). Analysis by solvent extraction is typically performed using carbon disulphide (CS₂) to extract the target VOCs from the adsorbent. Only a small aliquot of the CS₂ is subsequently injected into the GC; therefore, a longer period of exposure, or a higher uptake rate, are required to achieve comparable reporting limits.

Different chemicals have different adsorption properties, and a variety of adsorbent media are available. The selection of the appropriate adsorbent media should be done by consulting with an experienced analytical chemist. The goal is to provide a high degree of retention during sampling and good recovery during analysis. It may be impractical to design a single passive sampler suitable for the range of compounds of potential interest for VI investigations. Thermal desorption is typically used with weaker adsorbent materials (e.g., Tenax GC, Carboxen B), so the retention of less-sorptive VOCs may be low, especially over longer time periods or in areas of high concentrations (i.e., when the total mass of all VOCs adsorbed leads to competition for adsorptive sites, which causes the less adsorptive compounds to be lost). Poor retention can be managed with some advance information about expected concentrations, and usually readings with a portable instrument such as a photoionization detector (PID) are sufficient to identify appropriate limits on the exposure duration to avoid saturation. For active adsorptive sampling, there are recommended safe sampling volumes (SSVs) for combinations of compounds and adsorbents (Supelco, 2011). A negative bias in the reported concentrations is common when the sample volume exceeds the SSV, which is attributable to poor retention by the sampler. For passive sampling, the volume of gas drawn through the adsorbent is unspecified, but the uptake rate multiplied by the exposure duration provides a value in units of volume, which could be considered an “equivalent sample volume” for comparison to the SSVs, and this can estimate a maximum exposure duration for a particular combination of chemical and adsorbent.

2.1.2 Passive Samplers – Physical Description

2.1.2.1 SKC Ultra™

The SKC Ultra™ (<http://www.skinc.com/prod/590-100.asp>) is a badge-type sampler with option for thermal or chemical desorption, which operates by diffusion through either a high-diffusion plastic cap with ~300 holes, or a low-uptake-rate cap with 12 holes (Figure 1). These devices have been used for industrial hygiene applications for many years, and can provide quantitative VOCs analysis of indoor air samples at the part-per-billion (ppb) level (Coyne, Kuhlman, and Pacolay, 2002; Hendricks, Roberts, and Schultz, 2002; Hendricks, 2003). In the Ultra II sampler, the adsorbent is shipped separately in a sealed vial to retain purity. The body establishes a one-dimensional diffusion profile through a known length and cross-section. The sampler is exposed for a measured time, and then the sorbent medium is transferred back into the vial for return shipment to the laboratory. Depending on the compounds of interest, this device is commercially available with

three types of sorbent media, Tenax TA, Chromosorb 106, and Anasorb GCB1, which can be analyzed by solvent extraction or thermal desorption. Columbia Analytical Services in Simi Valley, California, is one of the laboratories specifically listed by SKC as a specialty provider of the analyses of these devices, and was used for these analyses.



Figure 1. SKC Ultra Sampler (left), and high- and low-uptake caps (right).

2.1.2.2 Radiello®

This sampler has a two-dimensional (radial) geometry with a large cross-sectional area, and increases the uptake rate for greater sensitivity (lower reporting limits for a given exposure duration). This makes lower reporting limits possible at similar exposure periods in comparison to one-dimensional geometry (Figure 2). The sampler is made up of two concentric cylinders; the inner cylinder is a cartridge that contains an adsorbent medium surrounded by a stainless steel mesh. The outer cylinder is made up of microporous-sintered polyethylene through which the vapors diffuse, and is manufactured with different pore-sizes for adjusting the sampling rate. Calibration constants for the sampler can be determined experimentally for each analyte, or can be estimated from the physicochemical properties of the analytes. The Radiello® sampler is available in either solvent extraction or thermal desorption, and in two different housings (white and yellow) with slightly different uptake rates. The housings are interchangeable, so all four combinations are possible. Radiello® is patented by Fondazione Salvatore Maugeri-IRCCS, Centro di Ricerche Ambientali in Italy. The Radiello® sampler was used successfully in the Monitoring of Atmospheric Concentration of Benzene in European Towns and Homes (MACBETH) Study, which consisted of sampling and analysis of 3,600 samples, each representative of 5-day exposures, collected on six occasions from about 100 locations in each of six European cities (<http://www.fsm.it/padova/homepage.html>).

2.1.2.3 3M OVM 3500™

3M OVM 3500™ is adapted from the badge style of sampler that has been used for industrial hygiene monitoring for decades. The plastic body snaps together and holds a porous plastic outer layer (diffusive barrier) a fixed distance from a thin film coated with activated carbon (Figure 3). Diffusion occurs across the porous barrier and through air to the activated carbon. Solvent extraction of the carbon after a period of exposure is used as the sample preparation, and an aliquot of the extract is injected to a gas chromatography/mass spectrometry (GC/MS) for quantization. The large surface area provides a high uptake rate, which yields a good sensitivity. Conversely, this may exacerbate the starvation effect for passive sampling in low face velocity settings, such as passive soil gas sampling. This sampler is also the largest of the candidate samplers, which is a disadvantage

for fitting in passive soil gas probes and flow-through cells. No low-uptake option or thermal desorption option is available.

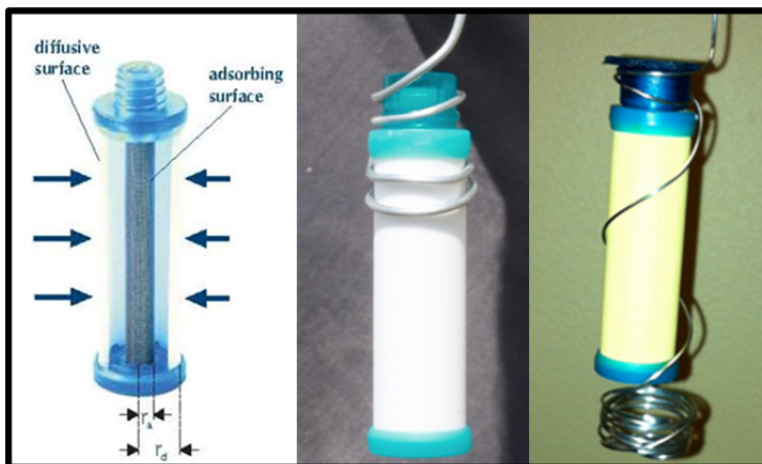


Figure 2. Radiello[®] sampler and high-uptake white and low-uptake yellow bodies.



Figure 3. 3M OVM 3500 passive sampler showing solid plastic cap used to replace a porous plastic sheet after sampling is complete.

2.1.2.4 Waterloo Membrane Sampler[™]

The WMS sampler is composed of a 1.8 or 0.8 mL standard crimp-top chromatographic auto-sampler vial partially filled with a known amount of sorbent and closed with a polydimethylsiloxane (PDMS) membrane of a consistent thickness (Figure 4). Uptake occurs through the PDMS membrane, which is highly resistant to moisture (which may interfere with the analysis) and to advective uptake attributable to turbulent flow (which can cause a positive bias under high velocity environments), so this sampler has advantages in wet or windy conditions.

The cross-sectional area and thickness of the membrane are controlled, providing a consistent and predictable uptake rate. The uptake rate can be calculated with reasonable accuracy for compounds similar to those for which it has been calibrated in controlled chamber experiments (Seethapathy and Gorecki, 2011 a, b). This calibration has been determined at different temperatures for 40 different compounds ranging from n-alkanes and aromatic hydrocarbons to alcohols and chlorinated organic compounds containing one to three carbon atoms. PDMS is used as a stationary phase on capillary

columns used in GC and the rate of diffusion through the PDMS membrane in the sampler is correlated to the GC linear temperature programmed retention index (LTPRI) of the analytes (a diagnostic property of chemicals reported in the scientific literature). Thus, the calibration constants can be easily estimated from the chromatographic retention times of the analytes. This makes it possible to estimate the concentrations of VOCs whose identity is unknown at the time of sampling and to quantify complex mixtures of analytes (e.g., petroleum fractions). The WMS sampler can be used with either chemical or thermal desorption to adjust the sensitivity and with different sized openings across the membrane to modify the uptake rates.

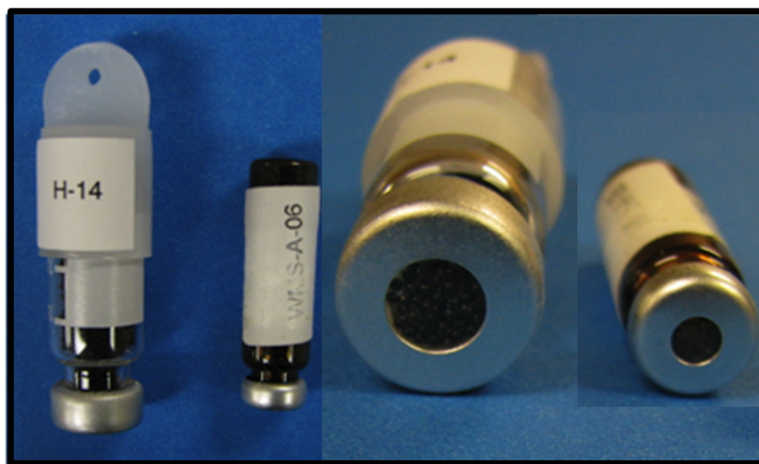


Figure 4. Waterloo membrane sampler showing two cross-sectional setups and close-up of membrane and adsorbent.

2.1.2.5 Passive ATD Tube Samplers

The automatic thermal desorption (ATD) tube samplers are available from various manufacturers, and consist of a standard ATD tube with a sealed and an open end (Figure 5). The open end can be fitted with either a dust screen cap or a smaller cross-sectional area cap to adjust the uptake rate. The ATD tube facilitates sample preparation, as it can be placed directly in the auto sampler of a thermal desorption unit for GC/MS analysis. Adsorbent media (e.g., Tenax TA, Carboxen B, and many others) are packed into the closed end and held in place with quartz wool. For sampling, the ATD tube is opened at the open end to expose the adsorbent to ambient VOCs (C_o), and a concentration gradient is created through the air inside the tube. The adsorbent is analyzed by thermal desorption, GC/MS or flame ionization detection (ATD/GC/MS&FID), as appropriate.

International standards are available describing the sampling procedure and the sampler performance assessment. The method for quantification of VOCs in indoor, ambient, and workplace air is described in international standard EN ISO 16017-2 (International Organization for Standardization, ISO, 2003). This standard provides guidance on the selection of appropriate sorbents for particular purposes where key considerations are the properties of the target analytes, the concentration of interest, and the required averaging time of the measurement. Selecting an appropriate sorbent relates predominantly to the volatility of the target analyte(s) and there is a requirement for the sorbent-analyte interaction to be appropriate to allow quantitative retention of the analyte, but also as the most efficient release possible when heat is applied in a flow of gas in the thermal desorber. EN ISO 16017-2 summarizes the published validation data (available in 2003) as a list of determined diffusive uptake rates for specific sorbent and analyte couples, identifying the level of validation undertaken. By far, most of the validations are for tests appropriate for workplace, with typical

concentrations in air near the occupational exposure limit, and exposure periods of 8 hours. The standard provides the diffusive uptake rate for over 50 VOCs determined for workplace monitoring, including a note on the level of method validation. There is also a summary of studies that determined uptake rates for indoor and ambient concentrations using exposure periods of between 1 and 4 weeks, with most of the data referring to benzene, toluene, ethylbenzene, and xylene (BTEX), which are volatile aromatic compounds typically found in petroleum, as well as data for trimethylbenzene, decane, and undecane. The ISO standard also recommends conditions for the thermal desorption of the different sorbents for the analysis by ATD/GC/MS&FID.



Figure 5. ATD sampler set for sub-slab sampling and regular and low-uptake-rate caps.

The closer the experimentally determined diffusive uptake rate is to the ideal value, the less likely that the method will be subject to biases due to effects of the environment. The stronger sorbents tend to also absorb water, which can be a problem in the analysis and can be limiting for some applications. Weaker absorbents such as Tenax do not retain water, but more volatile compounds are not strongly retained and may be lost from the sampling tube by back diffusion. These types of processes can result in non-ideal behavior of the samplers, where the performance of the sampler in the field may deviate from that calculated based on the dimensions of the sampler and the rate of diffusion of the analyte in air. When selecting a method, users often accept compromises on performance, particularly for the study of mixtures of compounds. For example, the sorbent Carboxen B may be optimal for benzene, but if the intention is to monitor a low-volatility compound at the same time (without the additional cost of using a separate sampler), then Tenax may be the preferred choice. This is because while its performance for determining benzene is compromised to some extent due to back diffusion losses from the tube, giving a lower effective diffusive uptake rate, it can also be used at the same time to determine compounds that would be poorly recovered on heating when using a strong sorbent.

The standard also discusses the impact on sampler performance of environmental conditions, such as humidity, air velocity, temperature, pressure, and occurrence of transient concentrations. Assuming the correct sorbent is selected, the standard advises that in practical use, the three main considerations are air velocity, protection from precipitation, and security. The samplers perform as designed in locations with low air movement (e.g., 5 cm s^{-1}), but if placed outdoors, an appropriate shelter should be used because precipitation, direct solar heating, and high-wind velocities may adversely affect performance.

The measurement of benzene in ambient air is the subject of a specific European standard (EN14662-4:2005) for diffusive sampling with ATD tubes. This standard describes the sampling and analytical procedure and provides performance data in terms of the expected overall uncertainty of the method. The document was prepared under mandate from the European Commission to establish a method appropriate for the measuring of benzene in ambient air to check compliance with the Air Quality Directive. Unfortunately, this same level of extensive validation is not available for other analytes in ambient air. This can be managed by using inter-method duplicates as a quality assurance/quality control (QA/QC) measure in a sampling program (for example 1 in 10 duplicates using a SummaTM canister/TO-15), which will provide field-verification of the uptake rates for detectable chemicals under the site-specific conditions.

Passive ATD methods were used for over a decade in the United Kingdom, particularly for indoor air monitoring (Brown et al., 1981, 1992; Brown and Crump, 1998; Crump et. al., 2004), but are relatively unused in North America. With regard to soil gas, the Environment Agency has supported published research on the use of pumped sampling with ATD tubes to determine VOCs in landfill gas.

2.1.3 Advantages of Passive Samplers

Passive diffusive samplers offer at least four potentially significant advantages to the current industry standard sampling approach of SummaTM canister sampling and TO-15 analysis.

Lower Cost. SummaTM canisters can cost up to about \$1000 to purchase, costs that are typically passed along as a rental charge. Flow controllers are required for time-averaged sample collection, and a rental charge is also levied to cover their purchase, cleaning, and certification. SummaTM canisters are much larger and heavier than passive samplers, which make them much more expensive to ship back and forth to a field site than passive samplers, because courier charges are based on size and weight. SummaTM canisters are re-useable, but they must go through an expensive cleaning and certification, and record keeping process required to maintain QA/QC needed for VI investigations, all of which is costly. Most of the passive samplers are disposable, except for ATD tubes, and are intended for a single use.

Simpler Sampling Protocols. Passive samplers are much easier to deploy than SummaTM canisters. Indoor air sampling with SummaTM canisters requires several steps: remove dust-cap, attach vacuum gauge, open and close valve, record vacuum reading to assess whether canister leaked en-route to a site, remove vacuum gauge, attach flow controller, open valve, record time, return at a later time, close valve, remove flow controller, attach vacuum gauge, open and close valve, record final vacuum and time, replace dust-cap, complete sample form, and ship to laboratory. Soil gas sampling adds additional steps for purging prior to sample collection, and this may be complicated in low permeability soils, where flow rates may not be sufficient for continuous purging and sample collection. By contrast, the passive samplers are considerably simpler to use, typically shipped clean and sealed in air-tight containers that are opened, placed in appropriate locations, left for a specified period, resealed, labeled, and returned to the laboratory. For soil gas sampling, it may not be necessary to purge, which simplifies the sampling process. The passive samplers are very similar to devices currently used for monitoring radon, which are most often deployed, retrieved, and shipped by homeowners. If building occupants can deploy the passive samplers, then this may substantially reduce costs associated with mobilizing trained professionals for sampling programs. Simplicity may also help to minimize bias and variability attributable to inter-operator errors.

Long-Term Samples. Passive samplers can collect samples for a longer time than SummaTM canisters. Concentrations measured with passive samples represent time-weighted average conditions over the sample collection, and minimize short-term temporal variability associated with changes in

weather conditions. These measurements are more representative of long-term average human exposures, which are the basis of health risk assessment. For vapor intrusion investigations, target concentrations based on 25- to 30-year average exposures are typically the basis for decision-making. Sampling and analytical methods that are affected by short-term temporal variability are undesirable because they either: (1) increase uncertainty, or (2) require additional sampling and analysis to characterize the expected degree of variability and support statistical calculations of long-term average concentrations.

Less Obtrusive. Passive diffusive samplers are small enough to be held in the palm of a hand, and look fairly simple and unobtrusive (Figure 6). Summa™ canisters are much larger (6-L canisters are about the size of a bowling ball), and are therefore much more obtrusive.



Figure 6. Setup of a pair of Summa™ canisters connected to a single intake valve used for demonstration. For size comparison, a 3M OVM 3500 passive sampler is on the top-right corner.

2.1.4 Limitations of Passive Samplers

Passive diffusive samplers have at least a few potential limitations relative to the current conventional sampling methods.

Starvation Effect. When the air velocity near the sampler is low, the sampler may remove VOC vapors faster than they are replenished, imposing a localized reduction in air VOC vapor concentrations. This results in a negative bias in the reported concentrations, which is referred to as the “starvation effect.” In indoor and outdoor air sampling, the face velocity is usually high enough to minimize starvation, except perhaps for the high-uptake-rate samplers. In soil gas sampling, particularly in low-permeability materials, the flow rate of soil gas will be very low or nil, which increases the risk of negative bias via starvation. The magnitude of the starvation effect is proportional to the uptake rate of the sampler, and there may be a minimum threshold uptake rate below which starvation is negligible. Assessment of this effect was accomplished using samplers with different uptake rates as part of this demonstration.

Saturation/Retention. If passive samplers are exposed to high concentrations for an extended time, then the adsorbent media may become saturated, in which case, the uptake rate may diminish. In addition, more strongly adsorbed compounds may displace less strongly adsorbed compounds, which could impose a negative bias on the concentration measurements for compounds with poor retention.

This can be managed with some advance information about expected concentrations, and usually readings with a portable instrument such as a PID are sufficient to identify appropriate limits on the exposure duration to avoid saturation. For active adsorptive sampling, there are recommended SSVs for combinations of compounds and adsorbents, and if the sample volume exceeds the safe sample volume, it is common to see a negative bias in the reported concentrations attributable to poor retention by the sampler. For passive sampling, the volume of gas drawn through the adsorbent is unspecified, but the uptake rate multiplied by the exposure duration provides a value in units of volume, which could be considered an “equivalent sample volume” for comparison to the SSVs, which can be used to estimate a maximum exposure duration for a particular combination of chemical and adsorbent.

Matching Adsorbent Media to Target Compounds. Different chemicals have different adsorption coefficients, and a variety of adsorbent media are available. The selection of the appropriate adsorbent media should be done by consulting with an experienced analytical chemist. The goal is to provide a high degree of retention during sampling and good recovery during analysis. It may be impractical to design a single passive sampler suitable for the range of compounds of potential interest for VI investigations. This is similar to challenges of conventional active sampling methods that employ ATD tubes, where sometimes several adsorbents are used in series in a single tube. For example, vinyl chloride is weakly retained by adsorbents, and may pose a greater challenge to the samplers than other VOCs; however, some semi-VOCs are so strongly adsorbed that may not be readily desorbed during analysis. Multiple passive samplers with different adsorbents may be deployed at a single location to capture the range of compounds of potential interest where the compounds of interest include very strongly and very weakly adsorbed compounds.

Unplanned Uptake of Chemicals. The passive samplers can become contaminated by unplanned exposure to chemicals during shipping and storage. The risk is reduced by carefully packing the samplers in containers resistant to VOC vapors. The potential can also be evaluated and documented by including trip blanks (samplers that travel continuously with the investigative samples, but are never removed from the packaging) in the sampling program.

2.2 BUILDING PRESSURE CONTROL

2.2.1 Building Pressure Control – Technology Description

When using indoor air sampling to evaluate VI, an investigator must address two confounding issues: (1) indoor sources of VOCs, and (2) temporal variability in VI. The evaluation procedure addresses both of these issues using a streamlined investigation program that can be completed during a single 3-day sampling event. This streamlined investigation protocol uses induced negative building pressure to ensure that vapor intrusion is “on” during one sample event and induced positive building pressure to ensure that vapor intrusion is “off” during a second sampling event (Figure 7). Because radon is a naturally occurring tracer for soil gas, radon concentrations in indoor air can be used to verify the effectiveness of the induced building pressure for controlling the movement of soil gas into the building. VOC concentration results for indoor air and ambient air samples collected during these two sample events are used to identify the primary sources of detected VOCs.

For this project, the Pressure Control Investigation procedure was demonstrated in six buildings. The results indicate that small (approximately 1 Pa) pressure gradients are sufficient to control the flow of soil gas through the building foundation. VOC concentrations measured in indoor air under these controlled building pressure conditions can be used to identify the primary source of the VOCs and to evaluate the potential for vapor intrusion for a range of building pressure conditions. These

results validate the use of the streamlined investigation procedure for evaluating vapor intrusion at sites where a building-specific investigation is required.

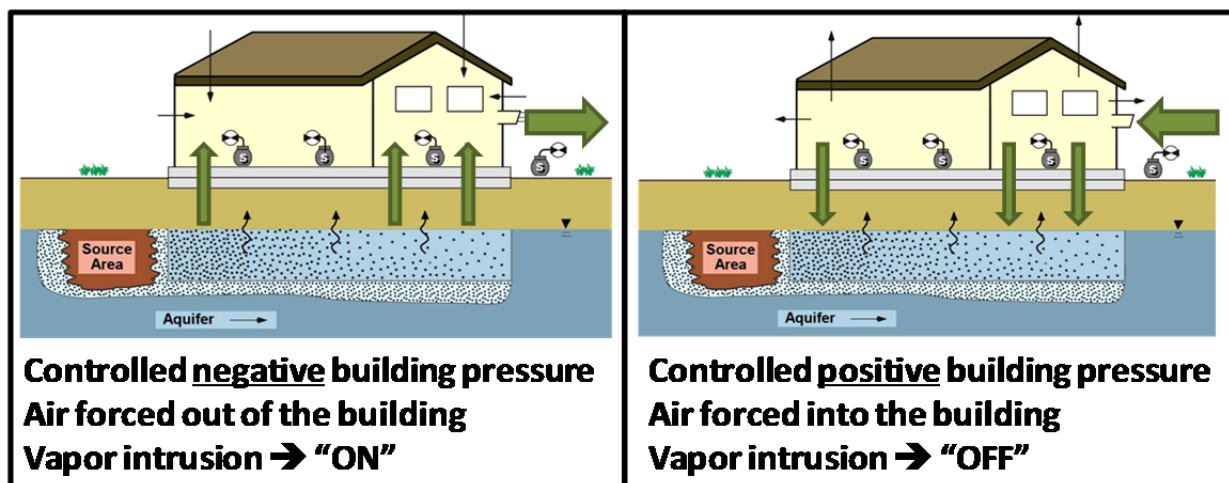


Figure 7. Conceptual illustration of building pressure control for building-specific assessment of vapor intrusion.

2.2.2 Advantages of Building Pressure Control

At sites where a field investigation is required to determine the presence or absence of a vapor intrusion impact, currently available guidance does not clearly define the required scope of the field investigation. Many current guidance documents recommend that large amounts of data be collected over an extended time. Even at sites where the initial field investigation provides no evidence of a VI impact, long-term monitoring is sometimes required to demonstrate long-term protectiveness. At some sites, high levels of variability in VOC concentrations or sporadic detections of COCs in some samples have prevented a definitive determination of the presence or absence of a VI impact. At Hill AFB, for example, many residences were included in a long-term indoor air-monitoring program because occasional detections of site COCs in some residences cannot be definitively attributed to either VI or other sources. For these sites, a focused field investigation procedure that reduces the time period of the required field investigation while increasing the ability to determine the presence or absence of a VI impact can significantly reduce the time and expense associated with the field investigation.

2.2.3 Limitations of Building Pressure Control

The streamlined evaluation procedure is targeted towards characterizing and controlling the building-specific factors that contribute to variability in VOC attenuation and associated VI impacts. The method is not applicable to very large or very leaky buildings where the building pressure cannot be easily controlled. In addition, the pressure control method does not eliminate the spatial variability on VOC concentrations that is observed at many investigation sites. At some sites, this spatial variability can make interpretation of the monitoring results more difficult.

3. DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The performance objectives for the demonstration of the suite of passive samplers and the pressure control technologies are summarized in Table 1. A synopsis of these objectives is provided below.

3.2 PASSIVE SAMPLERS – DEMONSTRATION DESIGN

The objective of this demonstration is to assess the precision and accuracy of passive samplers for quantification of indoor and sub-slab gas vapors. This is achieved by comparison with samples collected with Summa™ canisters, the conventional active samplers. While passive samplers have been used for occupational monitoring for decades, their application to monitoring the low VOC concentrations in indoor and outdoor air attributable to VI is at a much earlier stage of development and is therefore the purpose of this demonstration.

3.2.1 Passive Samplers: Quantification Accuracy in Soil Gas, Indoor and Outdoor Air

This performance objective was assessed by comparison of measurements using the conventional Summa™ canisters and the five different passive samplers selected. Samples, even duplicates of the same sample, analyzed in a specific laboratory with the same method, are expected to have about 25% in relative percent difference (RPD). For this demonstration, Summa™ canisters and passive samplers were analyzed in different laboratories using different methods, and an RPD of 30% was considered successful in demonstrating that passive samplers provide an accurate measurement of VOCs in indoor and outdoor air.

Samples from soil gas provide more spatial variability. To account for this, an RPD difference <50% between passive samplers and Summa™ canister quantification is considered successful.

3.3 PRESSURE CONTROL – DEMONSTRATION DESIGN

The primary objective of this part of the demonstration study is to develop simple procedures for limited building-focused field investigation of the vapor intrusion pathway. This objective was met by performing the following tasks:

1. Collecting an extensive amount of data related to the specific site conditions that influence VOC attenuation factors at the test sites.
2. Collecting data in a consistent and comparable manner from sites with a broad range of site conditions (i.e., soil characteristics and building characteristics).
3. Analyzing this data to obtain a thorough understanding of how site-specific conditions influence vapor intrusion processes.
4. Documenting measurement and control of building pressure for evaluating VI impacts.

Specific performance objectives include: (1) collection of data representative of site conditions; and (2) evaluation of the data to validate improved vapor intrusion investigation procedures.

3.3.1 Building Pressure Control: Collection of Data Representative of Site Conditions

The collection of site data that represents site conditions was achieved by adhering to the sampling and analysis procedures. QA/QC samples were collected to allow for the evaluation of data precision, accuracy, completeness, representativeness, and comparability.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Passive Samplers Quantitative Performance Objectives			
Accuracy of VOC vapor concentration quantization in soil gas, indoor air, and outdoor air.	Concentration measurements using each passive sampler and Summa™ canisters as control, with sufficient samples to assess the effects of the key factors	A relative percent difference of 30% between passive sampler and Summa™ canister concentrations is considered successful for indoor and outdoor air. For soil gas sampling, a relative percent difference <50% is considered successful.	Results were successful where retention and starvation were managed by appropriate selection of adsorbents and uptake rates. Field-calibration of uptake rates for some compounds would improve the accuracy.
Cost	Professional time required for sampling, analytical fee, material costs, and shipping charges	Cost reduction is compared to conventional methods that are sufficient to justify potential costs associated with regulatory acceptance of the passive samplers.	Potential savings are significant compared to conventional sampling methods, especially for large sampling programs or periodic monitoring.
Passive Samplers Qualitative Performance Objectives			
Assess ease of use	Feedback from the field sampling personnel with practical experience	Limited training required to obtain high quality data.	Fully passive sampling has simpler procedures, and a short learning curve.

Table 1. Performance objectives. (Continued)

Performance Objective	Data Requirements	Success Criteria	Results
Pressure Control Quantitative Performance Objectives			
Collection of data representative of site conditions.	VOC concentrations in soil gas, indoor air, outdoor air, and building pressure gradients.	An RPD \leq 30% precision for field samples. A laboratory precision RPD \leq 25%. As well as Completeness, Representativeness, and Comparability	Quantitative objectives were achieved with minor exceptions, typical of any significant environmental field program. The data quality for the demonstration program data set is acceptable and suitable for evaluation of the demonstration performance.
Validation of investigation procedure Hypothesis: Manipulation of building pressure to create negative and positive building pressures alters the distribution of VOCs in and around the building in a way that helps distinguish VI from background sources.	1) Measurement of VOC in indoor air and sub-slab gas under negative and positive building pressure conditions 2) Measurement of pressure gradients across building foundation and envelope, and in shallow soils below building	A statistically significant difference in VOC distribution between negative pressure conditions and positive pressure conditions	ANOVA demonstrates a statistically significant difference in VOC distribution in indoor air between negative and positive pressure conditions ($p = 0.03$). The change in VOC concentration in indoor air was different depending on the source of the VOC (i.e., above ground or subsurface). However, the predicted change in VOC concentration in sub-slab samples was not observed.
Pressure Control Qualitative Performance Objectives			
Development of validated investigation procedure	Field-tested investigation procedures	Procedures for implementation of streamlined investigation	Procedures for implementation of streamlined investigation were validated

3.3.1.1 Data Requirements

QA/QC samples were collected to ensure that the collected data represent site conditions. The specific QA/QC samples collected vary based on type of sample and analysis method, but typically include field duplicates, field blanks, and standard laboratory QA/QC samples. Field duplicate samples are collected at a minimum rate of 1 per 20 samples or 1 per sample event, whichever is greater.

3.3.1.2 Success Criteria

QA/QC samples were evaluated to determine the data precision, accuracy, completeness, representativeness, and comparability. These criteria include a precision objective for the field samples of an RPD $\leq 30\%$, and laboratory precision at RPD $\leq 25\%$.

3.3.2 Validation of Building Pressure Control Investigation Procedure

The hypothesis for validation of the streamlined investigation is that manipulation of building pressure to create negative and positive building pressures alters the distribution of VOCs in and around the building in a way that helps distinguish VI from background VOC sources.

3.3.2.1 Data Requirements

Validation of the field investigation methods will require: (1) manipulation of building air flow to create negative and positive building pressures; and (2) observation of differences in VOC distribution between negative and positive building pressure conditions. At each demonstration building, the distribution of VOCs and tracer gases in and around the test building was characterized, at a minimum, by collecting samples from three sub-slabs, three indoor, and one ambient air sample point under negative and positive building conditions. In addition, foundation permeability was evaluated by measuring pressure gradients across the building foundation and across the building envelope.

3.3.2.2 Success Criteria

The objective will be considered met if a statistically significant difference in VOC distribution is observed between negative pressure and positive pressure building conditions.

3.3.3 Development of Building Pressure Control Investigation Procedure

The goal of the field demonstration is to produce a validated and streamlined building-specific investigation procedure that provides a reliable determination of the presence or absence of a vapor intrusion concern for that building. The evaluation procedure will consist of (1) control of building pressure to create negative and positive building pressure conditions, (2) VOC and tracer gas sampling program, (3) pressure gradient measurements, and (4) data interpretation methods.

3.3.3.1 Data Requirements

Development of the streamlined evaluation procedure will require (1) validation of the investigation, and (2) feedback from field personnel concerning how the procedure can best be applied to other sites with vapor intrusion concerns.

3.3.3.2 Success Criteria

The objective will be considered as met if a simple protocol is developed that provides (1) procedures for control of building pressure, sample collection, and measurement of pressure gradients, and (2) guidance for data interpretation to determine the presence or absence of a vapor intrusion concern.

4. SITE SELECTION

The following criteria were used to identify potential demonstration sites.

Groundwater Contamination. A demonstration site must have a plume of dissolved VOCs, preferably with one or more chlorinated solvents with concentrations measured in nearby monitoring wells above $100 \mu\text{g L}^{-1}$. Note that chlorinated VOC concentrations measured at the top on the water-bearing unit are often lower than those measured in traditional monitoring wells. Therefore, if monitoring data are available for the top of the water-bearing unit, lower VOC concentrations (e.g., $10 \mu\text{g L}^{-1}$) are acceptable.

Site Characterization. A site should be well characterized about site hydrogeology and the nature and extent of dissolved contaminants. A site characterization report should be available providing delineation information for the dissolved plume near the test area and soil boring logs or monitor well logs that document geologic conditions in the test area.

Building Access. Access to the building at any time required for setting up and collection of samples is required. Areas the size of the top of an archive cabinet is required for sampling with passive samplers and SummaTM canisters. Access to the test building must be available for installation of several (three to six) test points through the building foundation. These test points will be 1-inch diameter or less and can be located in storage closets or other out-of-the-way locations. Building access should be available to conduct a 1- to 3-day test involving manipulation of building pressure by using the building heat, ventilation, and air conditioning system (HVAC) system, window fan, or blower, and the collection of indoor air and sub-slab gas samples.

4.1 SITE DESCRIPTIONS

The demonstration sites, selected based on the selection criteria described above, are listed in Table 2. Each of these sites has a dissolved chlorinated solvent plume in shallow groundwater that has migrated away from the source area. Prior to the demonstration, each site had been investigated in sufficient detail to describe the site geology and contaminant distribution and identify appropriate investigation buildings.

4.1.1 Hill Air Force Base

Arizona State University (ASU) purchased a house south of Hill Air Force Base in Layton, Utah, to study vapor intrusion under the Strategic Environmental Research and Development Program (SERDP) Project ER-1686 (Figure 8 and Figure 9). The “ASU Research House” was used for the demonstration of pressure control at Hill AFB. The building is an unoccupied single-family dwelling with a partially below-grade finished basement and single-story living space above the basement.

4.1.2 Marine Corps Air Station Cherry Point

Building 137 at Marine Corps Air Station (MCAS 137) Cherry Point located in Cherry Point, North Carolina, was used for demonstration of passive samplers for indoor air and outdoor air field sampling (Figure 10 and Figure 11). VOCs were previously detected in the soil vapor and groundwater during on-going Navy remedial investigations. Two indoor air samples were collected before the demonstration for verification of VOC concentration using 3M OVM 3500TM samplers between 3-4 November 2010, in the northern area of Building 137. TCE, 1,1,1-trichloroethane (111TCA), 1,1-dichloroethane (11DCA), benzene, toluene, and xylenes were detected at

concentrations ranging between 1.8 to 40 $\mu\text{g m}^{-3}$ in the two indoor air samples. Based on these results, the northern corner of Building 137 was identified as a viable field demonstration site for the collection of indoor air samples.

Table 2. Demonstration sites.

Site Name	Site location	Type of Demonstration	Support for Demonstration
Hill Air Force Base (AFB)	Layton, UT	Pressure Control	NESDI, ESTCP, U.S. EPA ETV
Marine Corps Air Station (MCAS 137) Cherry Point	Cherry Point, NC	Passive Samplers	NESDI
Moffett Field Naval Air Station (NAS)	Moffett Field, CA	Pressure Control	NESDI, ESTCP, U.S. EPA ETV
Naval Air Station (NAS), Jacksonville	Jacksonville, FL	Passive Samplers, Pressure Control	ESTCP
Parris Island Marine Corps Recruit Depot (MCRD)	Parris Island, SC	Pressure Control	ESTCP
Tinker Air Force Base (AFB)	Oklahoma City, OK	Pressure Control	ESTCP
SSC Pacific Old Town Annex to Building 3	San Diego, CA	Passive Samplers	NESDI
Travis Air Force Base (AFB)	Fairfield, CA	Pressure Control	ESTCP



Figure 8. Front view of ASU Vapor Intrusion Research House in Layton, Utah.

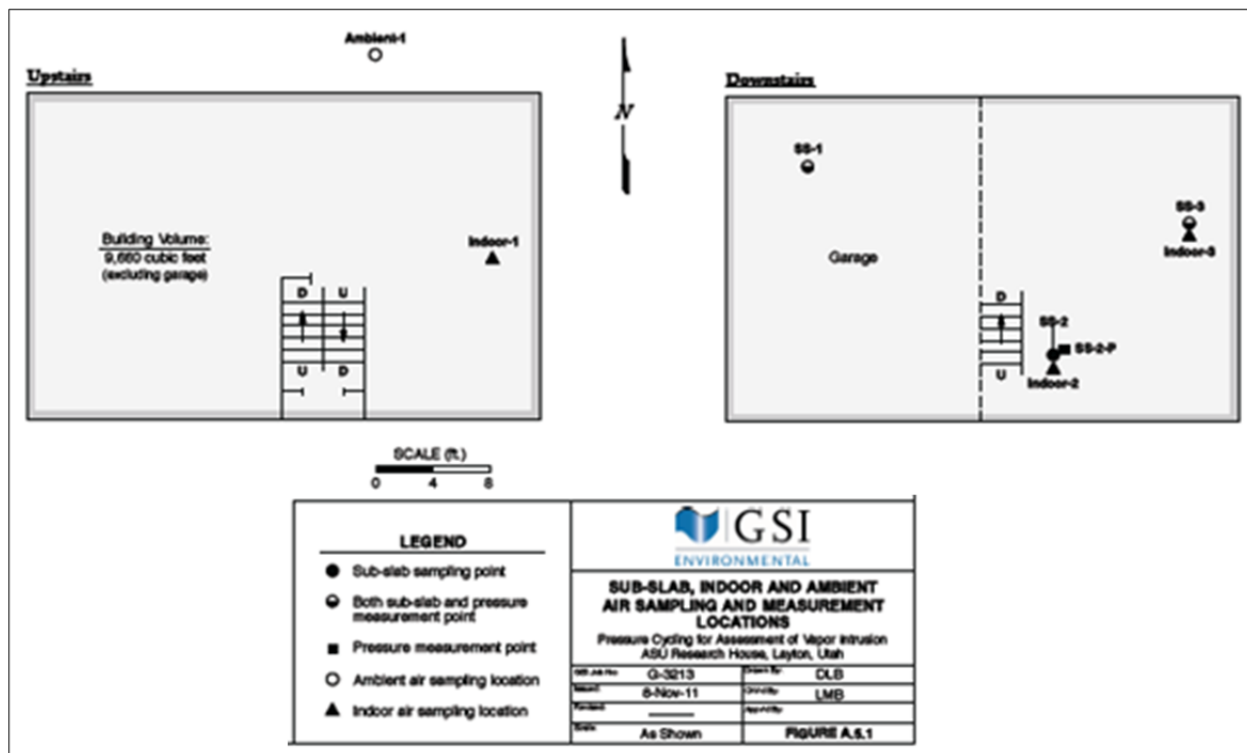


Figure 9. Diagram of ASU Vapor Intrusion Research House in Layton, Utah, with locations of sampling points for pressure control demonstration.



Figure 10. Diagram of MCAS 137 with sampling locations.

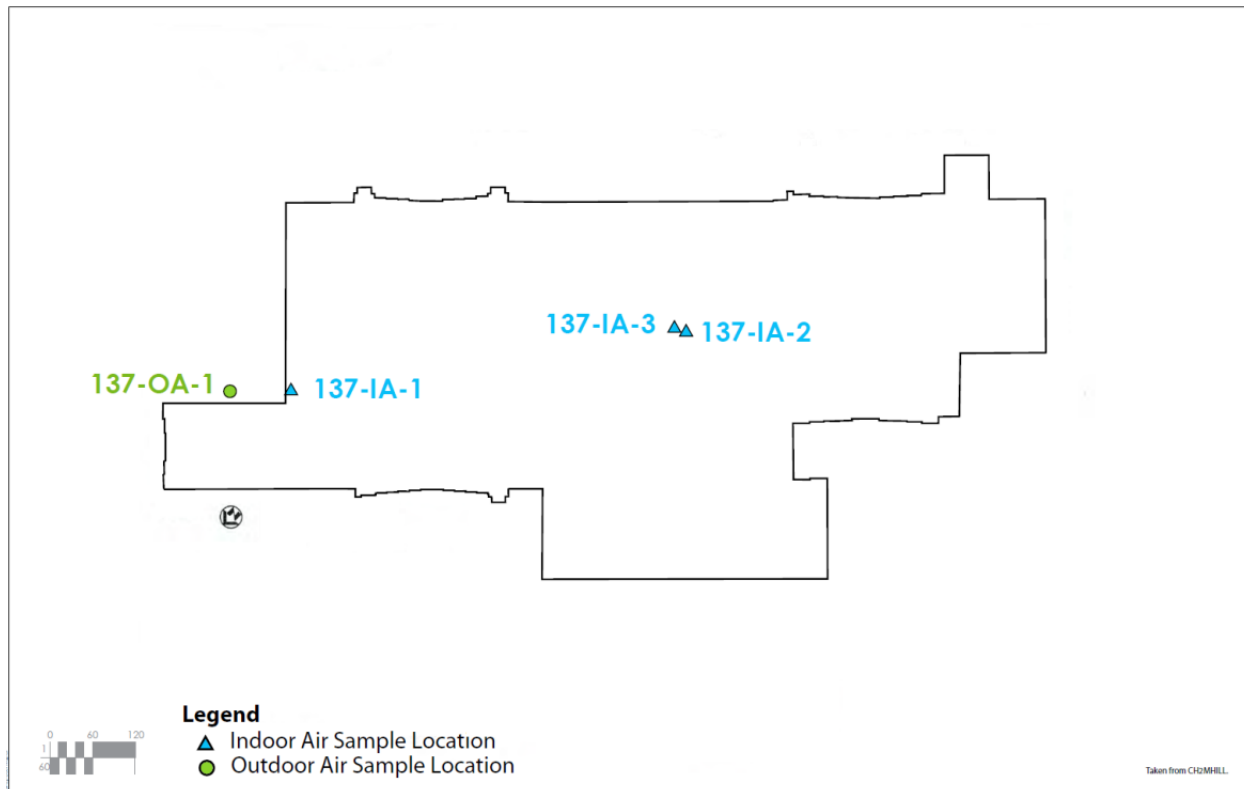


Figure 11. Diagram of MCAS 137 with sampling locations.

4.1.3 Moffett Field Naval Air Station

A demonstration of pressure control was conducted at Building 107 at the Moffett Field Naval Air Station (NAS) near Palo Alto, California (Figure 12). Building 107 is a single-story slab-on-grade structure. The building is in use by U.S. Navy personnel primarily during office hours. A diagram of Building 107 at Moffett Field with sampling locations is shown in Figure 13.



Figure 12. Front view of Building 107 at Moffett Field Naval Air Station.

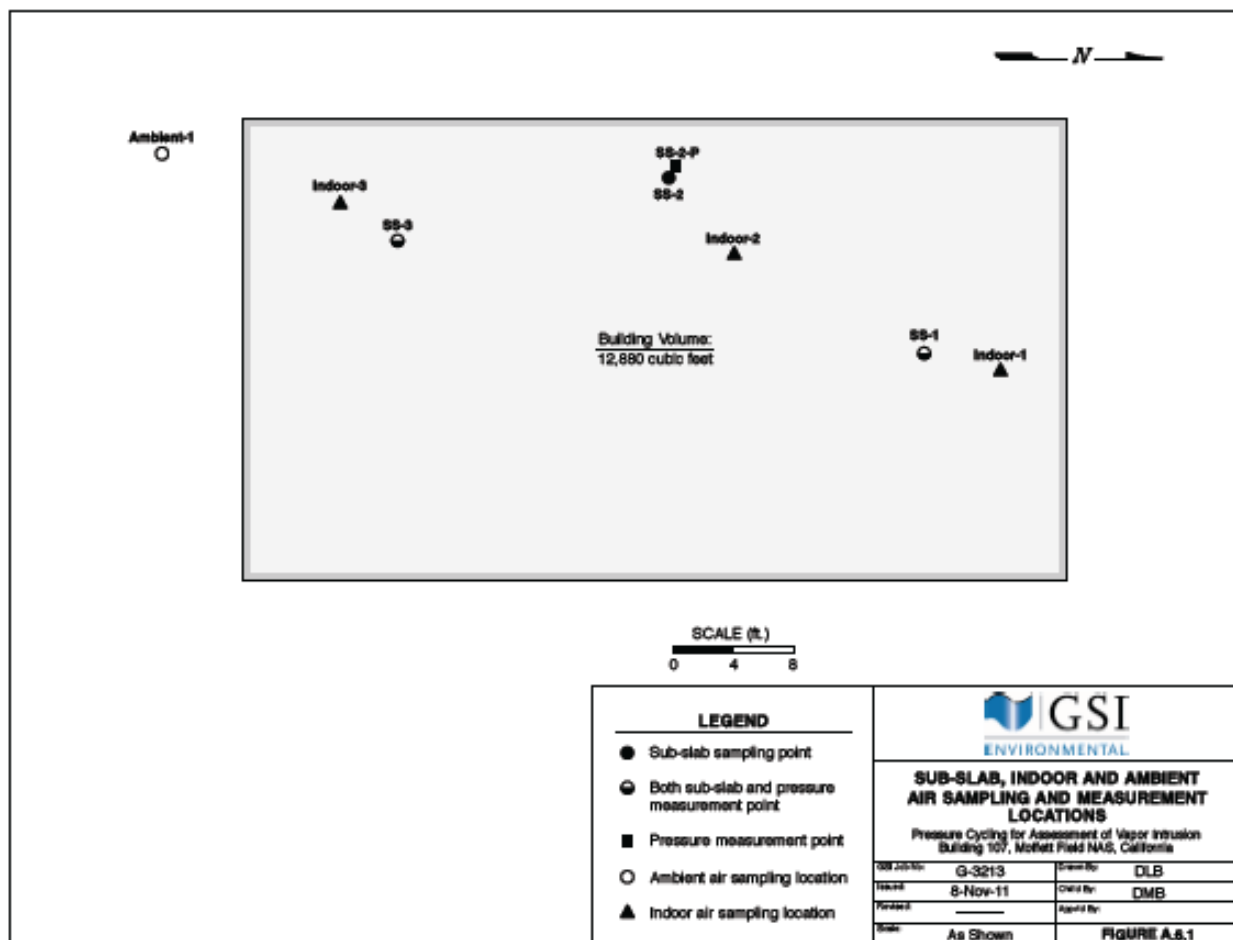


Figure 13. Diagram of Building 107 at Moffett Field Naval Air Station with sampling locations.

4.1.4 Naval Air Station Jacksonville

Building 103 at NAS Jacksonville (NAS JAX), Jacksonville, Florida, was used for demonstration of passive samplers for soil gas and sub-slab sampling, and for pressure control. A 5-year review (Tetra Tech, 2005) describes Operable Unit (OU) 3 as a 134-acre site with a former dry cleaner operation. Most of OU 3 was recently re-paved, and it is underlain by inter-bedded layers of sand, clayey sand, and clay. The water table at OU 3 is located within a few feet of ground surface. Groundwater Services Inc. (GSI, 2009) performed assessment of soil vapor concentrations and reported elevated VOC concentrations within soil and groundwater near Building 103. The primary COCs are tetrachloroethene (PCE), TCE, and related degradation products.

The demonstration was conducted in Building 103, a machine shop located within OU 3. The main portion of the building is 280 × 130 feet, with a secondary wing on the east side of approximately 240 × 60 feet. The building is slab-on-grade with a concrete foundation and was constructed in stages beginning in the 1940s.

Due to the relatively large size of Building 103, the investigation focused on one corner of the building, the southwest corner. This part of the building is closest to the areas of documented shallow soil gas impacts and is underlain by high levels of TCE, PCE, and degradation products in soil and groundwater. A diagram of NAS JAX Building 103 with sampling locations is shown Figure 14.

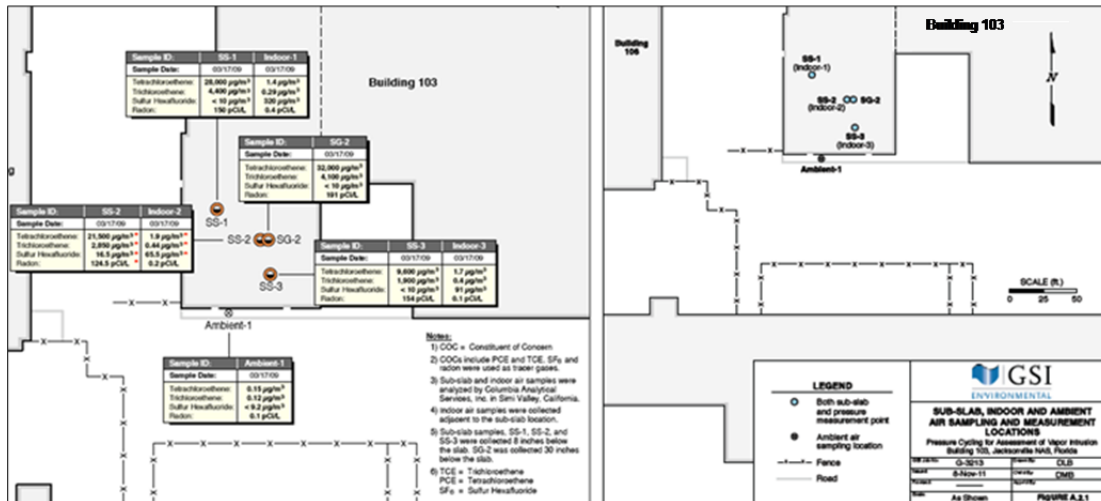


Figure 14. Diagram of Building 103 in Naval Air Station Jacksonville, Florida, with sampling locations, and sub-slab and indoor air data on the left reported by GSI Inc. (2009).

4.1.5 Marine Corps Recruit Depot Parris Island

A demonstration of pressure control was conducted at the new dry cleaning facility at Marine Corps Recruit Depot (MCRD) Parris Island, SC. This building is 120 × 70 feet with a ceiling height ranging from 15 to 25 feet. When originally opened, this facility was operated as a dry cleaning facility using petroleum-based cleaning solvents (i.e., no PCE or other chlorinated solvents). However, at the time of the demonstration, on-site dry cleaning operations had been terminated and the facility was used as a dry cleaning drop station for off-site cleaning. The off-site cleaner was using PCE-based cleaning solvent and, as a result, the clothing being stored on-site for customer pick-up was an indoor source of PCE. In addition, the building contained large ventilation slats in the walls along with ceiling vents that could not be completely closed. These ventilation structures were not identified during the building selection process. Because of building construction, building pressure control could not be achieved during the demonstration. A building diagram of the area of study is shown in Figure 15.

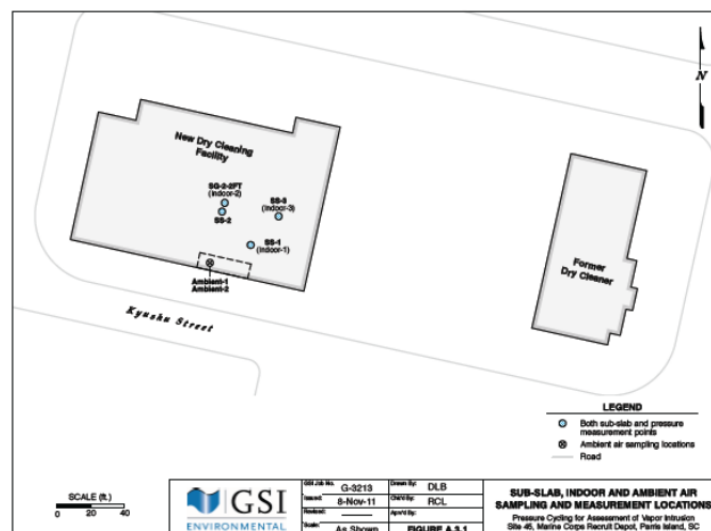


Figure 15. Diagram of new dry cleaning facility at Marine Corps Recruit Depot (MCRD) Parris Island, South Carolina, with sampling locations.

4.1.6 SPAWAR Systems Center Pacific Old Town Campus

The Annex to Building 3 at SSC Pacific Old Town Campus (OTC3), located in San Diego, California, was used as field sampling site for passive samplers (Figure 16). Previous site assessments (CDM, 2009) identified the presence of VOCs in groundwater and soil vapor samples near the north end of Building 3. As an initial verification, three indoor samples and one outdoor air sample were collected using Waterloo Membrane Samplers (WMS) between 17 December 2009 and 4 January 2010. TCE was detected at concentrations ranging between 3.3 and 4.6 $\mu\text{g m}^{-3}$ in the three indoor air samples, and was not detected above the laboratory reporting limit (0.59 $\mu\text{g m}^{-3}$) in the outdoor sample. Based on these results, OTC3 was identified as a viable field demonstration site.

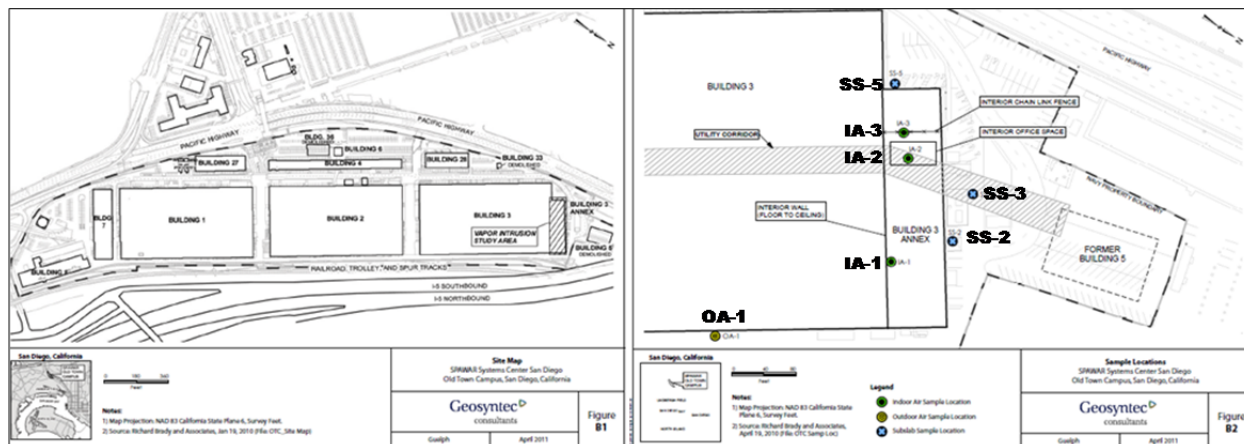


Figure 16. Diagram showing SSC Pacific OTC3 vapor intrusion study area (left) and sampling point locations (right).

4.1.7 Tinker Air Force Base

A demonstration of pressure control was conducted in the mechanical room of Building 200 of Tinker AFB. The mechanical room is not continuously occupied and is physically isolated from the remaining portion of the building, with only one door providing a connection. A building diagram is shown in Figure 17.

4.1.8 Travis Air Force Base

Pressure control was demonstrated in Building 828 at Travis AFB. The building is a former security forces armory in the Western Industrial Operable Unit (WIOU). The building was not occupied at the time of the demonstration. A diagram of Building 828 is shown in Figure 18.

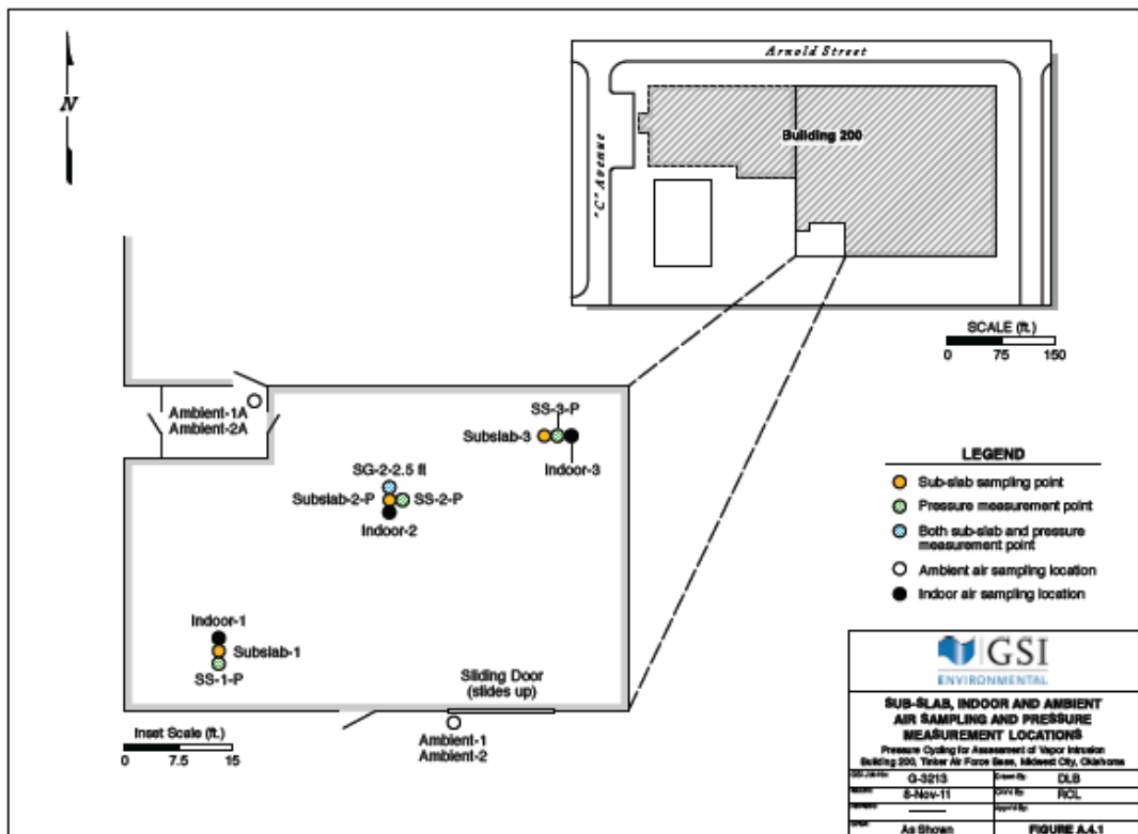


Figure 17. Diagram of Building 200 at Tinker AFB, with sampling locations.

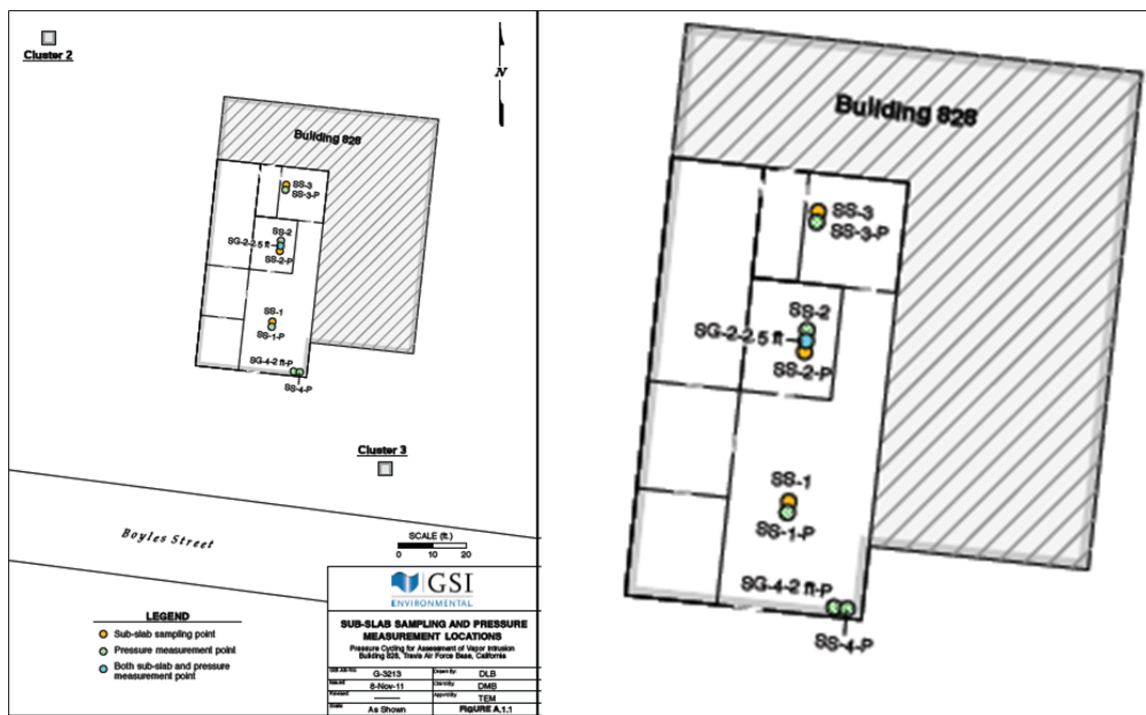


Figure 18. Diagram of Building 828 at Travis AFB with sampling locations.

5. TEST DESIGN

5.1 PASSIVE SAMPLERS – TEST DESIGN

The demonstration involved comparing five types of quantitative passive diffusive samplers (listed below) with conventional active samplers (Summa[™] canisters and analysis by U.S. EPA Method TO-15; U.S. EPA, 1999a). The comparison was based on indoor air, outdoor air, and/or soil vapor samples collected at MCAS, OTC3, and NAS JAX.

The following five passive samplers were evaluated:

- Waterloo membrane samplers[™] (WMS) (Seethapathy and Górecki, 2010a,b)
- Radiello[®] samplers (Radiello[®]) (Cocheo et al, 1996)
- 3M OVM 3500[™] badge samplers (3M OVM) (3M, 2013)
- Automated thermal desorption (ATD) tubes (Crump, 2009)
- SKC Ultra II[™] badge samplers (SKC) (SKC, 2012, 2013, Hendricks, 2003)

The scope of work for the demonstration included the following:

- Collection of air samples using five passive samplers and one active sampler at three locations inside and one location outside OTC3 (March 2010)
- Collection of sub-slab vapor samples using five passive samplers and one active sampler at three locations (two passive and one semi-passive) outside OTC3 (March 2010)
- Collection of air samples using five passive samplers and one active sampler at three locations inside and one location outside MCAS 137 (January 2011)
- Collection of sub-slab vapor samples using five passive samplers and one active sampler at three locations inside Building 103 at NAS JAX (January 2011)
- Only three passive samplers were tested because it was impossible to drill holes through the floor large enough to accommodate the 3M OVM and SKC samplers
- Collection of soil gas samples from 2-inch-diameter soil gas probes outside Building 103 at NAS JAX (January 2011)
- Performance assessment of the passive samplers by comparison with the results from active samplers
- Assessment of the cost of using passive samplers versus using active samplers

5.1.1 Passive Samplers Methods

This section describes the sampling methods for indoor and outdoor air samples, passive and semi-passive sub-slab samples, and passive soil gas samples.

5.1.1.1 Indoor and Outdoor Air Sampling

The indoor air samples were located in areas that would not be disruptive to building operations, within different sized areas (e.g., enclosed rooms or warehouse areas) that would have different building air circulation rates. The outdoor air samples were located in areas that provided some protection from precipitation, high winds, and direct sunlight. All samples at each location were collected in reasonably close proximity (i.e., within a few feet, but not so close as to impose interference between them) and about 3 to 5 feet above the floor surface (approximately the breathing zone). The passive samples were placed on shelves or hung and secured using thin gauge wire, then deployed according to the instructions provided by the manufacturer. Summa[™] canisters were placed on shelves in close proximity to the passive samplers (Figure 19).



Figure 19. Example of sampling array for demonstration of passive samplers for indoor air VOC assessment (OTC3).

Indoor air samples were collected in triplicate, using three of each of the five passive sampler types and three Summa™ canisters. Indoor air samples were collected in three indoor air locations at OTC3 and MCAS 137, nine of each type of sample. Outdoor air samples were collected in triplicate at OTC3, but the results were mostly below the limit of detection, so outdoor air samples at the MCAS 137 site were collected as single samples. At both sites, the outdoor air samples were collected using five passive sampler types and one Summa™ canister. Following review of the results of the first indoor air sampling event, some changes were made to the selected adsorbents for each of the samplers with options for customizing. Specifically, to minimize the risk of poor retention, ATD tubes and SKC Ultra samplers were changed from Chromasorb 106 to Carbopack B and Carbograph V, respectively, which are both stronger adsorbents. To increase sensitivity and provide lower reporting limits, Radiello® and WMS samplers were changed from solvent extraction to thermal desorption, as summarized in Table 3.

For the deployment of the active samplers (deployed in triplicate) at OTC3, one individually certified 6-L Summa™ canister and one batch-certified Summa™ canister were connected in parallel, via a sampling tee provided by the laboratory, to a 3-day flow controller (Figure 19). This allowed for the continuous collection of a sample for 6 days. Only the individual-certified Summa™ canisters were analyzed. For the deployment of the active samplers (deployed in triplicate) at MCAS 137, one individually certified 6-L Summa™ canister was connected to a 7-day flow controller.

5.1.1.2 Sub-Slab Vapor Sampling

Sub-slab vapor samples were collected from three locations at both San Diego OTC3 and NAS JAX. The OTC3 locations were selected to span a range of VOC concentrations and the NAS JAX Building 103 samples were collected to be similar to the locations previously sampled by GSI. The methods used at each of the sites are described in the sections below.

Underground Utilities. At OTC3, Navy Public Works Center Utilities Group, Underground Service Alert, and a private utility locating service cleared underground utilities (water, sewer, electrical, gas, phone, etc.) at each of the proposed sub-slab sample locations prior to drilling. At NAS JAX, sub-slab utility locations had previously been mapped prior to probe installations by GSI (GSI, 2009).

Table 3. Number of passive samplers used in each demonstration, as well as type of sorbent and laboratory desorption method.

Sampler	Uptake Rate	Sorbent	Desorption Method	Navy OTC3, San Diego, CA				MCAS, Cherry Point, NC		NAS, Jacksonville, FL		
				Indoor Air	Outdoor Air	Fully Passive Sub-slab	Semi-Passive Sub-slab	Indoor Air	Outdoor Air	Fully Passive Soil Vapor	Temporary Soil vapor	Fully Passive Sub-slab
Summa™ canister	NA	NA	TO-15	3 × 3	1 × 3	2 × 1	1 × 1	3 × 3	1 × 1	2 × 10 1 × 15		3 × 1
3M OVM	Regular	Charcoal	Solvent	3 × 3	1 × 3	2 × 1	1 × 1	3 × 3	1 × 1	1 × 7		NS
ATD	Regular	Chromosorb	Thermal	3 × 3	1 × 3	2 × 1	1 × 1					
		Carbopack B	Thermal					3 × 3	1 × 1	1 × 7		
	LUR	Carbopack B	Thermal									3 × 1
WMS	Regular	Anasorb 747	Solvent	3 × 3	1 × 3	2 × 1	1 × 1					
		Carbopack B	Thermal					3 × 3	1 × 1			
	LUR	Anasorb 747	Solvent							1 × 7	1 × 6	3 × 1
SKC	Regular	Chromosorb	Thermal	3 × 3	1 × 3	2 × 1	1 × 1					
		Carbograph 5	Thermal					3 × 3	1 × 1			
		Carbograph 5	Thermal							1 × 7		NS
Radiello®	Regular	Charcoal	Solvent	3 × 3	1 × 3	2 × 1	1 × 1					
	LUR	Carbograph 4	Thermal					3 × 3	1 × 1			
		Charcoal	Solvent							1 × 7		3 × 1

Each cell contains information on the number of locations times the number of samples in each location (i.e., 1 × 3 means one location with three samples, and 3 × 1 means three locations with one sample each). LUR is low uptake rate, which were set as follows: for ATD tube, a diffusion rate-reducing cap was added to open end of tube; for WMS and a amber vial, a smaller membrane surface area was used; for SKC, a 12-hole cap was positioned on face of sampler; for Radiello®, a yellow diffusive body was used. NS is No Sample, several unsuccessful attempts were made to core 2-inch-diameter holes (large enough to accommodate these samplers); therefore, these samplers were not deployed.

Initial Sub-Slab Vapor Screening. At OTC3, a temporary sub-slab probe was installed at each of five locations for field screening to assist in selecting the sample locations. Each temporary probe was installed by drilling a nominal ½-inch-diameter hole through the concrete slab using a hammer drill, inserting a piece of ¼-inch-diameter Nylaflow® tubing and sealing it with a non-toxic pliable putty (Sticky-Tac; Figure 20). Each probe was purged with three successive 1-L volumes using a vacuum chamber (a.k.a. “lung box”) and a Tedlar® bag and then field screened with a miniRae® 2000 PID that was calibrated in the field with isobutylene and zeroed using ambient (outdoor) air. After reviewing the PID screening results from each probe, three locations were selected for collection of the sub-slab vapor samples for the demonstration (SS-5, SS-2, and SS-3), corresponding to field screening readings of about 0.1, 10, and 100 parts per million by volume (ppmv), respectively. Upon completion of the screening, all holes through the concrete slab were sealed to the total depth drilled and finished flush to grade with fast-setting anchor cement.

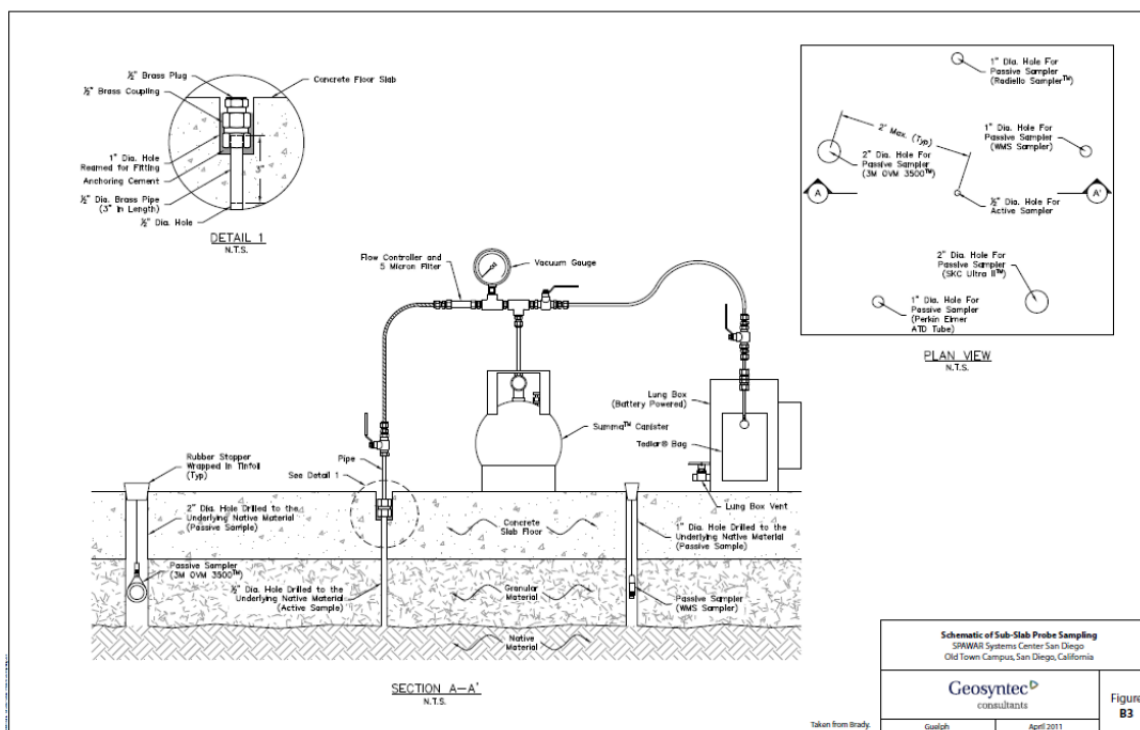


Figure 20. Schematic of sub-slab probe setting.

At NAS JAX, prior knowledge of the sub-slab vapor concentrations was available (GSI, 2009); PCE ranged from about 10,000 to 30,000 $\mu\text{g m}^{-3}$ and TCE ranged from 1,900 to 4,400 $\mu\text{g m}^{-3}$. These concentrations are detectable with relatively short passive sampler exposure durations (10 min or less, depending on the sampler’s uptake rate).

Sub-Slab Probe Installation. At OTC3, six holes were drilled through the concrete slabs in each of the three sub-slab sampling locations at OTC3, one for a conventional active sample, and one for each of the five passive samplers. The holes were configured with one in the middle for the active sample, and the other five in a circle around the central hole at a radius of about 2 feet (Figure 21). For the collection of the active samples, a nominal ⅝-inch-diameter hole was drilled through the concrete slab and reamed to a 1-inch diameter for the upper 2 inches. A nominal 3-inch length of ½-inch-diameter brass pipe and coupling was then placed in the hole and the annulus between the probe and the slab was sealed using anchor cement. For the passive sampling probes, a nominal 1.5-inch-

diameter hole was drilled, which is the minimum diameter that can be used for the 3M OVM sampler, and it was considered appropriate to have the same design for all of the passive samplers. The core was removed and the opening temporarily sealed with a nitrile glove stuffed with a few more gloves sufficient to exert pressure against the sidewalls to act as a cork and minimize air exchange prior to sampler deployment.



Figure 21. Sub-slab probe array (OTC3).

At NAS JAX, it was very challenging to drill a 2-inch-diameter hole through the floor slab because of the unexpected amount of steel reinforcing bars in the slab. After seven failed attempts at two locations using two different types of tools (hammer drill and rotary saw), time constraints forced a change in plans and 1-inch-diameter holes were drilled using the hammer drill at all three locations. As a result, the SKC and 3M OVM samplers could not be deployed in the sub-slab probes as planned because the outside diameter of these samplers is 1.25 and 1.75 inches, respectively.

Sub-Slab Probe Sealing at End of Deployment. Upon completion of the sampling, all holes through the concrete slab were sealed to the total depth drilled and finished flush to grade with fast-setting anchoring cement.

5.1.1.3 Fully Passive Sub-Slab Sampling

Prior to sample collection, each sub-slab probe was purged to remove any atmospheric air entrained during drilling/coring. Prior to purging at the active sample locations, a brass tee and ball valve were attached to the probe for purging. A shut-in test was then conducted to assess the potential for leaks in the above-ground fittings. Soil gas was purged from each probe (active and passive) using a vacuum chamber (i.e., lung box) and Tedlar[®] bag (Figure 22). Successive 1-L Tedlar[®] bags were analyzed using a ppbRae[®] PID to measure the total concentration of VOCs. These data were used to assess consistency in VOC concentrations between each of the six sampling locations in each area and to select an appropriate deployment time for the passive samplers.



Figure 22. Lung box used to purge sub-slab probes prior to passive sampler deployment.

The active samples were collected by 1-L batch certified Summa™ canister with a 200-mL min⁻¹ flow controller. A new piece of ¼-inch Nylaflo™ tubing was attached to the flow controller with a compression fitting for each location to minimize the risk of equipment blank contamination. After the lung box was used to purge the hole in the slab, the tubing connected to the Summa™ canister was inserted into the hole and sealed with a one-holed rubber stopper wrapped in aluminum foil. The Summa™ canister was open for about 4 min to collect a sufficient sample for analysis by EPA Method TO-15.

After purging the passive probes, the samplers were lowered to the bottom of the cored hole. Each sampler was wrapped with stainless steel wire to create a protective cage to protect them from contacting the soil below the slab. An additional length of stainless steel wire was used to make a tether to retrieve the sampler after deployment (Figure 23). The passive samplers were lowered into the cored hole immediately after purging, and the hole was sealed at the surface with a rubber stopper wrapped in a layer of Saran Wrap™ and a layer of aluminum foil. At OTC 3, the sample deployment time was overnight (~15 hours) for the location with a PID reading of about 0.1 ppmv (Location SS-5), 2 hours for the location with a PID reading of about 10 ppmv (Location SS-2), and about 10 min at the location with PID readings of about 100 ppmv (Location SS-3), which was estimated as sufficient time for all of the passive samplers to have detectable concentrations, assuming that the main compound detected by the PID was TCE and the uptake rates would not be significantly lower than the indoor air uptake rates for each sampler.

At NAS JAX, passive sub-slab sampling progressed as described for the OTC3 sampling event, except that lower uptake rate versions (i.e., smaller membrane surface area for chemicals to diffuse across) of the WMS, Radiello®, and ATD samplers were used, as follows:

- WMS samplers were 0.8-mL amber vials instead of 1.8-mL clear vials, which reduces the uptake rate because of a smaller opening in the aluminum crimp-cap
- Radiello® samplers used the lower uptake rate yellow body
- ATD tubes were fitted with the low-uptake rate cap



Figure 23. Deployment of a fully passive ATD tube sample showing wire basket used to prevent contact with soil at the bottom of the cored hole, steel wire tether for retrieval, and rubber stopper wrapped in aluminum foil used as a temporary cap.

Samples in Summa™ canisters were collected in the middle of the passive sampler deployment, in case there was any appreciable change in vapor concentrations over time. However, PID readings were stable for the sub-slab probes during 10-12 January, so the Summa™ canister samples are considered representative for both earlier and later passive samples. Summa™ canister samples were collected by sealing a 1/4-inch Nylaflo tube a few inches down the hole with blue Sticky-Tack (which was previously confirmed to provide a good seal and not contribute detectable concentrations of VOCs to the sample). The probe was purged via the lung box and PID screening was performed to verify stable readings before Summa™ canister collection.

5.1.1.4 Semi-Passive Sub-Slab Sampling

At OTC3, location SS-3 had high concentrations (~100 ppmv on the PID), amenable to a short-term (i.e., 10 min) exposure of the passive samplers. Short-term deployments risk dilution of the sampling environment by air-exchange during sample placement that may not recover fully during the short exposure period. To avoid dilution issues, these probes were sampled using a “semi-passive” method. Rather than using a stopper wrapped in foil to seal the cored hole during passive sampler deployment, the holes were sealed using a one-hole rubber stopper, and the PID was used to draw a modest flow through the stopper. This resulted in a slow continuous flow of soil gas past the sampler, which should have minimized any negative bias from incomplete purging or atmospheric air entrainment during sample deployment, as well as to minimize any negative bias from the starvation effect.

5.1.1.5 Fully Passive Soil Gas Sampling

Many regulatory guidance documents call for soil gas samples outside a building to be collected at a depth of at least a few feet and, preferably, 5 feet or more below ground. At NAS JAX, the water table was encountered at a depth of about 4.5 feet, so samples were collected between 3 and 4.5 feet below grade. In some cases, it is also useful to collect a series of samples over time. Therefore, a set of soil gas samples was collected at NAS JAX to evaluate the performance of the passive samplers in semi-permanent probes. For a comparative study, the diameter of the probe needs to be large enough to accommodate the largest sampler (the 3M OVM is the largest diameter and requires a nominal 2-inch-diameter probe); therefore, the passive soil gas probes were constructed of a 3-foot length of 2-inch-diameter PVC casing, similar to a groundwater monitoring well, except instead of a well-screen and filter-pack, the well casing was suspended above the bottom of the hole with stilts

(Figure 24). This design allows the samplers to be exposed to a void space surrounded by bare soil. Three soil gas probes were installed along the western side of Building 103, immediately north of the southwest corner. The probes were installed in 4-inch-diameter, hand-augured holes, which stood open without caving. The probes were installed with void spaces 6, 12, and 18 inches long, corresponding to void volumes of 1, 2, and 3 L, respectively, to assess whether the program design was effective.



Figure 24. Passive soil gas probe showing aluminum stilts used to suspend the pipe above the bottom of the augured hole and the plastic sleeve that was filled with tamped sand to seal the borehole annulus, both of which are secured with a stainless steel ring clamp.

A plastic sleeve formed an annular seal above the void space. The annular seal was constructed by placing fine sand into the annulus between the 2-inch PVC well pipe and the 5-inch-diameter plastic sleeve, and tamping the sand with a wooden dowel to cause the plastic sleeve to expand out to the wall of the 4-inch-diameter borehole. After placing the seal, each probe was purged until PID readings stabilized, then left capped overnight to equilibrate. A close-up of the top of the well-cap is shown in Figure 25.



Figure 25. Cap of passive soil gas probe with fittings for purging line (extends to just below cap) and Summa™ canister sampling line (extends through 1/8-inch stainless steel tubing to bottom of PVC pipe).

Passive soil gas samplers were suspended by nylon line attached to the bottom of the slip cap and cut to a length just longer than the PVC pipe, so the sampler was suspended in the open region below the pipe during sampling. Three sampling durations of 20, 40, or 60 min were used to assess the influence of sample duration. Immediately after the passive samplers were deployed and the slip-caps secured, purging was conducted until PID readings were nearly stable through a compression fitting in the top of the well-cap. PID readings were made continuously during purging by placing the PID at the outlet of the purging pump and allowing excess flow to vent, so as not to pressurize the intake of the PID, or allow the PID to draw any appreciable amount of outdoor air. PID readings were consistently within the range of 1.0 to 1.5 ppmv for all three probes and generally stabilized within about 20 to 30 sec on average. Purge rates were at about 3 L min^{-1} , so the purge volume was typically about 1 to 1.5 L, which corresponds to about 1 casing volume for the probe pipe. The time required to reach stable PID readings was sometimes longer when the wind was stronger, which caused more air exchange within the probe during the brief period (5 to 10 sec) that the slip cap was removed to retrieve and deploy two successive passive samplers.

The Summa[™] canister sample was collected immediately after purging via a $\frac{1}{8}$ -inch stainless steel drop-tube that extended to a similar depth as the passive sampler (Figure 26). The canister was filled quickly (~ 10 seconds) so that the passive sampler would not be biased by any flow during most of the sampling period.



Figure 26. Collection of soil gas samples with Summa[™] canisters.

Two passive samplers were exposed for longer than planned because they did not immediately come up out of the probes. In one case, an ATD tube sample was hanging at an angle and bridged under the PVC pipe until it was released using a wooden dowel to assist with aligning the sampler (SG-FP-60-1-ATD was deployed for 69 min instead of 60 min). The other case was a 3M OVM sampler, for which the hook connecting the nylon line to the bottom of the cap at the top of the probe became dislodged and needed to be fished out of the probe (SG-FP-60-3-OVM was deployed for 66 min instead of 60 min). For both of these samples, the concentrations of all detected compounds were within the range measured in other samples from the fully passive sampling data set, so there is no clear reason to exclude these data.

ATD tubes were deployed without the planned low-uptake rate cap because PID readings were somewhat lower than expected and a low-uptake rate may have resulted in no detectable concentrations for the planned deployment times of 20, 40, and 60 min.

Care was taken to ensure the diffusive surfaces of the passive samplers did not directly contact the geologic materials. WMS and ATD tubes were completely wrapped in aluminum mosquito mesh secured with stainless steel wire, and Radiello® was wrapped with a coil of stainless steel wire, with a short wire coil underneath the sampler (Figure 27).



Figure 27. Radiello®, WMS, and ATD samplers wrapped to protect them from contact with soil.

SKC samplers packed with Carbograp 5 were used instead of charcoal, as planned, because the charcoal samplers were not in stock, and the 12-hole (reduced uptake rate) cap was used to minimize the starvation effect. The 3M™ OVM samplers were used as supplied by the manufacturer. The WMS samplers were the low uptake variety with solvent extraction analysis.

5.1.2 Laboratory Analysis

All samples were analyzed by Air Toxics of Folsom California, except Radiello® samplers used for the passive soil gas sampling at NAS JAX, which were analyzed by Fondazione Salvatori Maugeri of Padova, Italy, and Summa™ canisters for San Diego OTC3 samples, which were analyzed by Columbia Analytical Services of Simi Valley, California. The Summa™ canister samples were analyzed by EPA Method TO-15 (U.S EPA, 1999a) for sub-slab and soil gas samples and the indoor and outdoor air samples were analyzed by EPA Method TO-15 (U.S EPA, 1999a) using selected ion monitoring (SIM). The passive samplers were analyzed by carbon disulfide extraction followed by GC/MS (solvent extraction samplers) or by EPA Method TO-17 (U.S EPA, 1999b) (thermal extraction samplers). One trip blank sample was collected and analyzed for each passive sampler type at each site. The trip blanks were prepared and shipped with the investigative samples, but were not opened in the field.

The samples were analyzed for site-specific compounds of interest for each of the following sites:

- OTC3: TCE, PCE, cis-1,2-dichloroethene (cDCE), trans-1,2-dichloroethene (tDCE), 1,1-dichloroethene (11DCE), and vinyl chloride (VC)
- MCAS 137: TCE, PCE, 111TCA, 1,1,2-trichloroethane (112TCA), 11DCA, 11DCE, 1,2-dichloroethane (12DCA), cDCE, tDCE, and BTEX
- NAS JAX: cDCE, 11DCE, PCE, and TCE

5.2 BUILDING PRESSURE CONTROL – TEST DESIGN

The purpose of this field demonstration is to validate the use of control of building pressure in a streamlined evaluation of vapor intrusion. Validation of the streamlined evaluation methods required application of the method at a number of buildings to demonstrate that building pressure control provides a clear determination of vapor intrusion conditions for buildings of different size, design, and foundation characteristics.

The impact of building pressure on VI is illustrated in Figure 7. The sampling program for the validation of the streamlined evaluation procedure is summarized in Table 4 and the field schedule is provided in Table 5.

Table 4. Summary of evaluation sampling program.

Component	Matrix	Number of Samples	Analyte	Location
Building Investigation (each test building)	Indoor air	6	Radon, sulfur hexafluoride (SF ₆), VOCs	Indoors, three locations during negative and positive pressure conditions
	Sub slab vapor	6	Radon, SF ₆ , VOCs	Sub-slab, three locations during negative and positive pressure conditions
	Ambient air	1	Radon, SF ₆ , VOCs	Outdoors, upwind, once at each location
	Pressure gradient	NA	Differential pressure between indoor/outdoor and indoor/sub-slab space	Continuous sampling at various sample points during positive and negative pressure conditions

Note: Additional samples collected for some demonstrations.

Table 5. Field demonstration schedule pressure control.

	Tasks	Day 1	Day 2	Day 3
1.	Sample point installation			
2.	SF ₆ release and pressure measurement			
3.	Depressurization start/equilibration			
4.	Collection of depressurization samples: VOCs			
5.	Collection of depressurization samples: radon			
6.	Pressurization start/equilibration			
7.	Collection of pressurization samples: VOCs			
8.	Collection of pressurization samples: radon			

5.2.1 Design and Layout of Technology Components

At each candidate site selected for the field demonstration, the field program consisted of: (1) installation of sampling points; and, (2) field testing and collection of soil gas and indoor/ambient air samples. The following sections describe the procedures used for installation of the sampling points, the field testing and sample collection procedures, and the analysis methods.

5.2.1.1 Installation of Sampling Points for Validation of Investigation Program

Sub-slab Sample Points. At each building selected for the demonstration, several sub-slab sample points were installed below the concrete slab using a hammer rotary drill with a 1-inch drill bit. Most sample points were completed just below the slab; however, one or more deeper holes were advanced at some sites using a $\frac{3}{4}$ -inch steel rod driven to a depth of 30 inches below ground surface. The sub-slab sampling points were constructed of $\frac{1}{8}$ - or $\frac{1}{4}$ -inch Nylaflow tubing lowered to the bottom of the borehole. A sand pack using U.S. mesh interval 20/40 sand was installed a few inches above the bottom of the borehole. The remainder of the borehole was filled with bentonite chips to the ground surface and hydrated to create an annular seal. Upon completion, the top of the borehole and the Nylaflow tubing were sealed from atmospheric air with modeling clay. An example of a completed sub-slab sampling point, and the sub-slab sampling point construction specifications are shown in Figure 28.

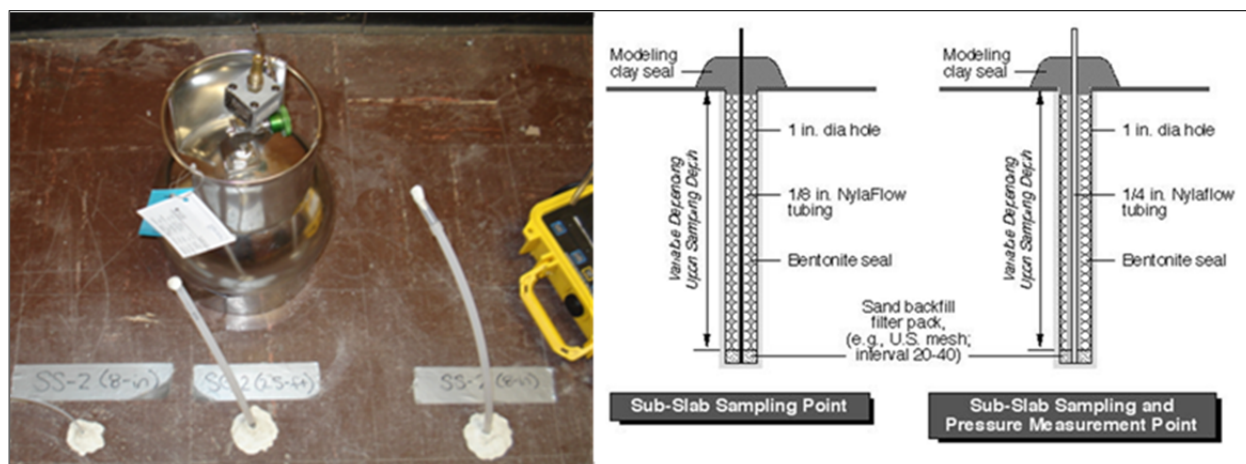


Figure 28. Example of sub-slab sample port and sample train, and construction specifications for sub-slab sampling points.

Indoor Sample Points. For each test building, three indoor air sample locations were selected to characterize the distribution of VOCs, radon, and sulfur hexafluoride (SF_6) tracer gas inside the building. Specific sample points were selected based on evaluation of building operating characteristics and were located to minimize the disturbance of building activities.

Outdoor Sample Point. For each test building, one air sample point was selected to characterize the concentration of VOCs, radon, and SF_6 tracer gas outside the building. The specific sample point was selected at an upwind location based on evaluation of building operating characteristics and prevailing wind direction.

Building Envelope Pressure Gradient Measurement Points. For each test building, one or more points were identified to measure the pressure gradient across the building envelope (i.e., ambient/indoor pressure gradient). At each measurement point, $\frac{1}{4}$ -inch tubing was installed across the

building envelope to allow measurement of the pressure gradient using a portable pressure transducer.

5.2.1.2 Field Testing

One or two rounds of field testing and sample collection were conducted at each demonstration site following installation of the sampling points. For validation of the evaluation procedure, the field testing program consisted of the measurement of cross-foundation and building envelope pressure gradients.

Measurement of Pressure Gradients. Pressure gradients across the building foundation compared to pressure gradients across the building envelope are used to evaluate the building foundation permeability. Pressure gradients were measured using an Omniguard 4 differential pressure transducer that is equipped with a data logger. The pressure transducer has two pressure ports, a reference port open to the indoor atmosphere, and a second port that is open to the area to be measured (sub-slab space or outside the building). The pressure transducer measures the pressure difference between the two ports, providing a differential pressure measurement. A photo of the pressure transducer installation is presented in Figure 29.

At the initiation of the testing program, the pressure gradient was measured at each sub-slab measurement point and at the building envelope pressure gradient measurement point. Pressure gradients at each measurement location were recorded for at least 1 min. During the collection of the composite samples for VOC analysis, continuous pressure gradient measurements were recorded every 5 to 15 min at one cross-foundation measurement point located near the center of the building and at one building envelope measurement point.



Figure 29. Set-up for cross-foundation measurement with a pressure transducer. Note that reference port is located to the right-hand side of the sub-slab connection on the Omniguard transducer.

5.2.1.3 Sampling Methods

Validating the evaluation procedure involved collecting and analyzing indoor air, ambient air, and sub-slab soil gas samples under negative pressure and positive pressure building conditions.

Induction of Negative and Positive Building Pressure. Negative and positive building pressures were created using a box fan in an outside window or door. Resulting pressure gradients were recorded. Each pressure condition was maintained for 12 hours before initiation of sample collection to allow the chemical concentrations to reach steady state.

Measurement of Building Air Exchange Rate. For five of the six demonstration buildings, a tracer gas, SF₆, was used to evaluate the indoor air exchange rate (i.e., the rate of air exchange between the building and ambient air). The indoor air exchange rate was measured by releasing SF₆ at a central location within the building and measuring steady-state SF₆ concentration at each indoor air sample location after 12 or more hours (Figure 30). At Tinker AFB Building 200, no tracer gas was used due to an error in obtaining the correct gas. In all buildings, the volume of air flow induced by the fan was calculated to provide an estimate of air exchange attributable to the pressure control system.



Figure 30. SF₆ tracer gas release system.

Collection and Analysis of Indoor and Ambient Air Samples. At each test building, indoor air samples were collected at three locations. At each location, a 6-L Summa™ canister was used to collect an 8-hour composite sample for analysis of VOCs and SF₆. A 500-mL Tedlar® bag was used to collect a grab sample for radon analysis. This sampling program was completed once during the negative pressure event and once during the positive pressure event.

At each test building, an ambient air sample was collected outside of the test building during each indoor air sampling event to serve as an ambient background sample. One 8-hour composite sample was collected for analysis of VOCs and SF₆ using a 6-L Summa™ canister, and one grab sample was collected using a 500-mL Tedlar® bag for radon analysis.

Collection and Analysis of Sub-Slab Gas Samples. At each test building, each of the three sub-slab sampling points was sampled during the two sampling events, for negative building pressure and positive building pressure. At each location, a 1-L or larger Summa™ canister was used to collect a grab sample for analysis of VOCs and SF₆. A 500-mL Tedlar® bag was used to collect a grab sample for radon analysis (Figure 31). The number of samples collected for each demonstration is provided in Table 4 and the analytical methods are provided in Table 6. The sample train used for sample collection is illustrated in Figure 28.

Table 6. Analytical methods used for sample analysis for pressure control.

Matrix	Analyte	Method	Container	Holding Time (Days)
Vapor	Radon	McHugh, Hammond, Nickels, and Hartman, 2008	Tedlar [®] bag	14*
	VOCs	U.S. EPA TO-15	Summa [™] canister	30
	SF ₆	National Institute for Occupational Safety & Health (NIOSH) Method 6602 (1994)	Summa [™] canister	30

* = No holding time specified, but lab tests demonstrate accurate results after 14 days storage in Tedlar[®] bag (McHugh et al., 2008).

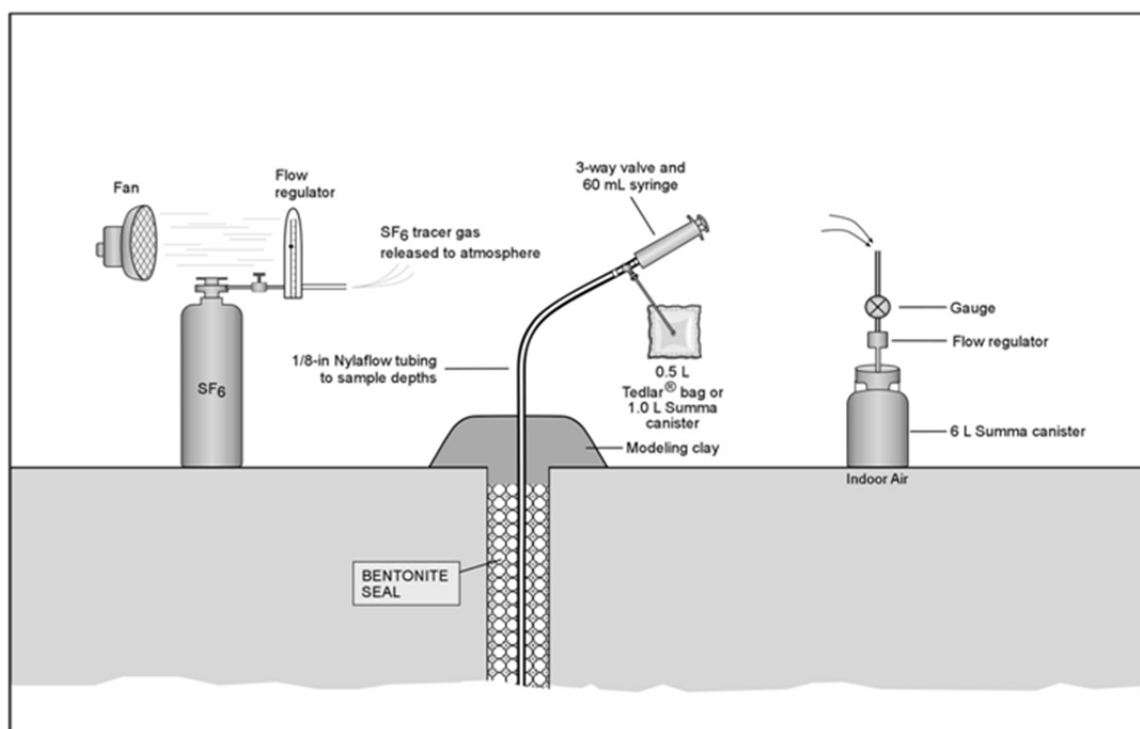


Figure 31. Collection of indoor and sub-slab samples for demonstration of pressure control.

6. RESULTS

6.1 PASSIVE SAMPLERS - RESULTS

This section presents and discusses the key results from each of the field sampling events as well as the key findings and lessons from the demonstration of passive samplers.

6.1.1 Building 3 at SSC Pacific Old Town Campus (OTC3)

6.1.1.1 OTC3 Indoor and Outdoor Air Results

Samplers were deployed in one location in an interior office and in two locations within the warehouse area of OTC3 on 9 March 2010, and retrieved on 15 March 2010 (Figure 16). The office was a small room with low (8-foot) ceilings. The warehouse area was chosen for two of the sampling locations because it is a large open area, in contrast to the interior office. The outdoor air sampling location was adjacent to the warehouse in an area that provided some protection from precipitation, high winds, and direct sunlight. No detectable results were reported in the San Diego trip blanks (Table 7). A discussion of the key observations is summarized below.

- Indoor air samples (Table 8) showed detectable concentrations of TCE in all samples and cDCE in all locations for those samplers with sufficiently low reporting limits (Radiello[®], SKC, and Summa[™] canister).
- Outdoor air samples (Table 9) showed no detectable concentrations of VOCs except PCE in the SKC samplers. PCE was detected in all indoor and outdoor samples collected by the SKC samplers and not in any of the other samplers. The SKC samplers had lower reporting limits for this compound than any of the other samplers, including the Summa[™] canisters.
- For TCE there is a good agreement in indoor air concentrations measured by the passive samplers compared to Summa[™] canisters, with most of the data falling within a $\pm 25\%$ agreement, except for the SKC sampler, which showed a substantial negative bias (Figure 32).
- For cDCE, the Radiello[®] samplers had good agreement with the Summa[™] canister in indoor air concentrations, and the SKC showed significant negative bias (Figure 33). The concentrations were below the reporting limits for the other passive samplers.
- There is a strong agreement between all the passive samplers and the Summa[™] canister for TCE measurements in indoor air, except for the SKC sampler (Figure 34).
- A summary chart of all the indoor air data (Figure 35) shows all of the passive samplers correlated strongly with the Summa[™] canisters, except the SKC sampler, which had a negative bias.
- The SKC Sampler was used with Chromosorb 106 as the adsorbent media. The safe sample volume (SSV) for TCE and cDCE on Chromosorb 106 is less than 5-L (Supelco, 2011). When collecting active samples in a pumped ATD tube, the SSV is the maximum volume of air that can be drawn through the ATD tube before breakthrough of the analyte may occur. The uptake rate for the SKC sampler for these compounds is about 15 mL min^{-1} (Table 8). The uptake rate has units of volume/time, but this is not to be construed as a flow rate. It is the flow rate that would correspond to the same concentration, sample duration, and adsorbed mass if an active (pumped) adsorbent tube sampler had been used. The samplers were deployed for about 7 days, and at an uptake rate of about 15 mL min^{-1} , the product of which can be thought of as an “equivalent” sampled volume, which would have been about 150 L. The equivalent sampled

volume is much larger than the safe sample volume, which indicates the low bias for the SKC samples is most likely attributable to poor retention.

6.1.1.2 OTC3 Sub-slab Sample Results

One of each of the five passive sampler types was deployed, and one conventional active sampler (Summa™ canisters) was collected at each of the three sub-slab sample locations (SS-2, SS-3, and SS-5) at OTC3 (Figure 16). The sub-slab sample locations were selected to have high (SS-3), medium (SS-2), and low (SS-5) concentrations of total VOCs, i.e., approximately 100 ppmv, 1 ppmv and <0.1 ppmv, respectively. A discussion of the key observations is summarized below.

- Sub-slab samples (Table 9) showed a wide range of TCE concentrations in Summa™ canister samples (450 to 560,000 $\mu\text{g m}^{-3}$), corresponding approximately to 0.1 to 100 ppmv, which is consistent with expectations based on the PID screening. cDCE concentrations were about five times lower than TCE concentrations, and tDCE concentrations were another order of magnitude lower.
- Sub-slab samples at locations SS-2 (Figure 36) were deployed passively for about 2 hours, and the results show that all the passive samplers had a negative bias relative to the Summa™ canister sample. The WMS and ATD samples showed less negative bias than the 3M™ OVM and the Radiello®, while the SKC was the most negatively biased. The negative bias is proportional to the uptake rate of the sampler and therefore is most likely attributable to the “starvation effect,” whereby the sampler removes VOCs from its surroundings faster than they are replenished, thereby causing depletion of the vapor concentrations during the sampling interval.
- Sub-slab samples at location SS-5 were deployed passively for about 15 hours, and the results show that all the passive samplers had a negative bias relative to the Summa™ canister (Figure 37). As with location SS-2, the negative bias was larger for samplers with higher uptake rates and is therefore attributable to the “starvation effect.”
- Sub-slab samples at location SS-3 (Figure 38) were deployed semi-passively for about 10 minutes. For the semi-passive sampling, the samplers were placed in the cored holes and a foil-lined stopper, with a 1/4-inch nylon tube through the middle, was connected to a PID, which was used to purge the hole at a flow rate of a few hundred milliliters per minute periodically during a 10-min sample deployment. This sampling approach resulted in much less negative bias for the high uptake rate samplers (3M™ OVM, SKC, Radiello®) and no apparent negative bias for the low uptake rate samplers (WMS and ATD), presumably because the purging of soil gas by the PID helped to minimize the “starvation effect,” although the higher uptake rate samplers still showed more negative bias than the low-uptake-rate samplers.
- PID screening during sample deployment also showed variability in PID field screening readings between the three probes at location SS-3 that were used to collect samples (Table 10). Figure 38 was not adjusted for the variation in PID readings, but this could be done by multiplying the passive sampler results by these Correction Factors (Summa™ sample location PID reading divided by passive sampler location PID reading). These factors are relatively low and would not substantially change the interpretation of Figure 38 because the data is on a logarithmic scale.

The samplers with the higher uptake rates (SKC, Radiello®, and 3M™ OVM) generally showed more negative bias in the fully passive samples than the samplers with the lower uptake rates (ATD and WMS). The relationship between the uptake rate and the “starvation effect” is further evaluated

in Figure 39, in which the “starvation factor” (Summa™ canister concentration divided by passive sampler concentration) is plotted versus the uptake rate (ideally, the starvation factor should be 1.0, indicating no bias). There is a positive correlation in Figure 39, although there is also some variation from sampler to sampler. Figure 39 indicates that low uptake rates (0.1 to 1.0 mL min⁻¹) may correspond to a low or negligible starvation effect for sub-slab sampling.

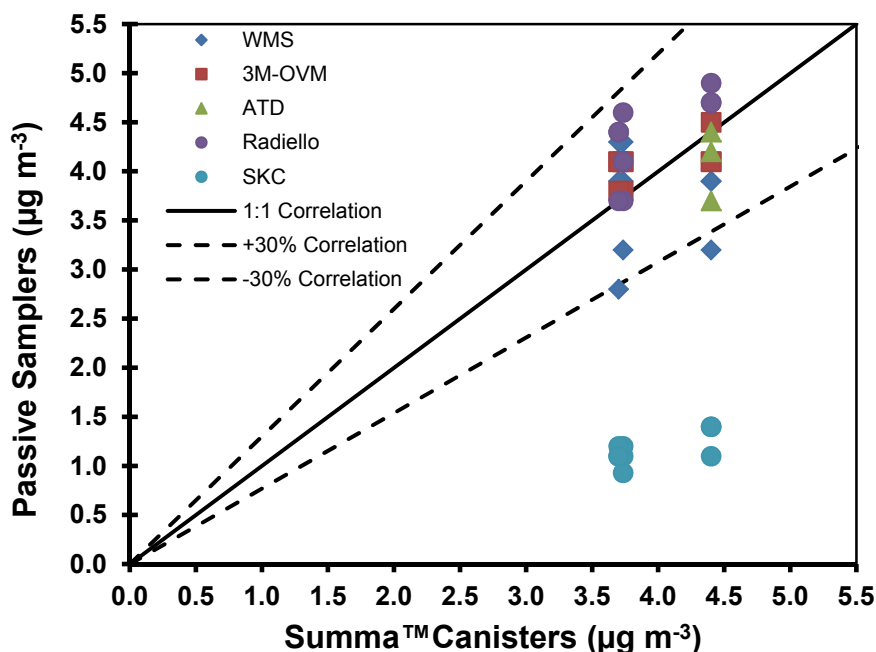


Figure 32. Correlation between passive samplers and Summa™ canisters for TCE (µg m⁻³) in indoor air at OTC3.

Table 7. Analytical results for trip blanks from the OTC3 demonstration effort.

Sample Type:	Trip Blank	Trip Blank	Trip Blank	Trip Blank	Trip Blank
Passive Sampler:	WMS	3M™	ATD	RAD	SKC
Deployment Date:	03/09/2010	03/09/2010	03/09/2010	03/09/2010	03/09/2010
Collection Date:	03/15/2010	03/15/2010	03/15/2010	03/15/2010	03/15/2010
Exposure Duration (minutes):	8400	8400	8400	8400	8400
VOCs (µg m ⁻³)					
1,1-Dichloroethene	29 U	1.0 U	1.0 U	0.61 U	0.035 U
cis-1,2-Dichloroethene	6.2 U	0.62 U	1.3 U	0.37 U	0.043 U
Tetrachloroethene	1.1 U	0.32 U	1.5 U	0.20 U	0.046 U
trans-1,2-Dichloroethene	9.0 U	0.64 U	1.3 U	0.39 U	0.044 U
Trichloroethene	0.73 U	0.29 U	1.2 U	0.17 U	0.040 U
Vinyl Chloride	50 U	0.86 U	1.8 U	NA	0.059 U

Notes: U is not detected; J is an estimated value; NA is not analyzed.

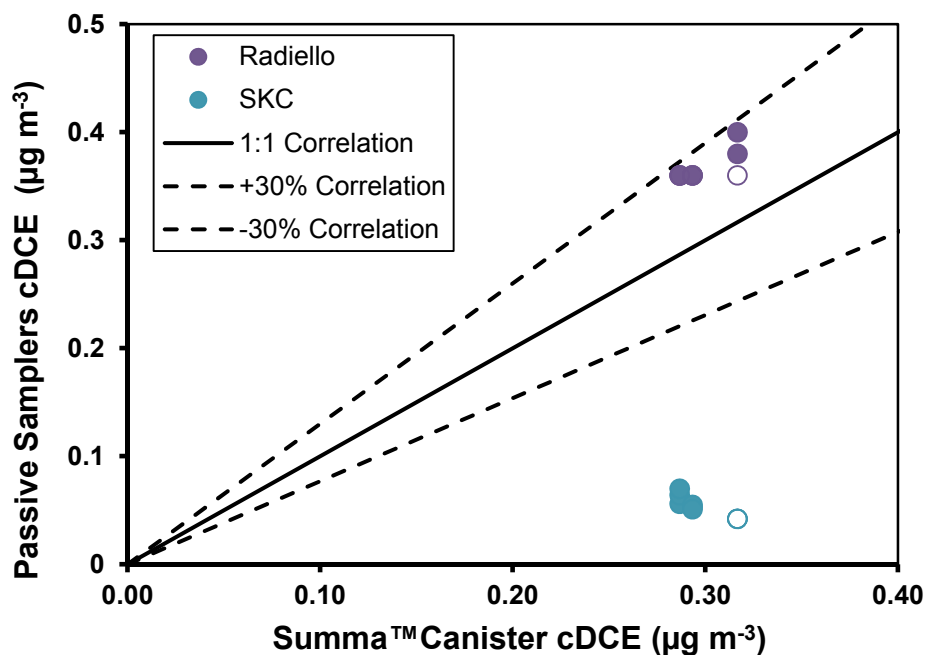


Figure 33. Correlation among passive samplers and Summa™ canisters for cDCE ($\mu\text{g m}^{-3}$) in indoor air from OTC3.

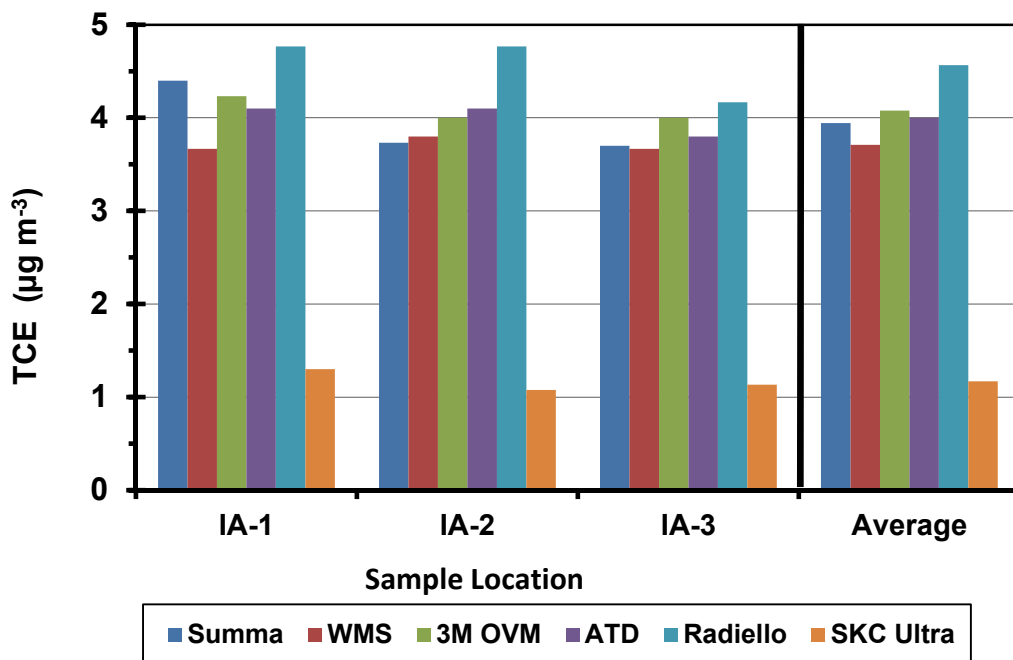


Figure 34. Stacked bar representation of TCE concentration ($\mu\text{g m}^{-3}$) in indoor air at OTC3. Bars to the left side (labeled IA-1, IA-2, and IA-3) are the average of the three samples collected at that location, and average bars to the right are the average indoor air concentrations at the three locations.

Table 8. Analytical results for indoor air (IA) and outdoor air (OA) from OTC3.

Sampler	Sample Location:	IA-1 ($\mu\text{g m}^{-3}$)			IA-2 ($\mu\text{g m}^{-3}$)			IA-3 ($\mu\text{g m}^{-3}$)			OA-1 ($\mu\text{g m}^{-3}$)		
	Sample ID:	IA-1A	IA-1B	IA-1C	IA-2A	IA-2B	IA-2C	IA-3A	IA-3B	IA-3C	OA-1A	OA-1B	OA-1C
Summa Canister	1,1-Dichloroethene	0.053 U	0.055 U	0.053 U	0.056 U	0.056 U	0.12 U	0.065 U	0.053 U	0.053 U	0.060 U	0.063 U	0.053 U
	cis-1,2-Dichloroethene	0.28	0.28	0.30	0.31	0.33	0.31	0.28	0.30	0.30	0.12 U	0.12 U	0.11 U
	Tetrachloroethene	0.18 U	0.19 U	0.18 U	0.19 U	0.19 U	0.42 U	0.22 U	0.18 U	0.18 U	0.21 U	0.21 U	0.18 U
	t-1,2-Dichloroethene	0.53 U	0.55 U	0.53 U	0.56 U	0.56 U	1.2 U	0.65 U	0.53 U	0.53 U	0.60 U	0.63 U	0.53 U
	Trichloroethene	4.9	3.7	4.6	3.7	3.8	3.7	3.4	3.8	3.9	0.16 U	0.17 U	0.14 U
	Vinyl Chloride	0.034 U	0.036 U	0.034 U	0.036 U	0.036 U	0.079 U	0.042 U	0.034 U	0.034 U	0.039 U	0.040 U	0.034 U
WMS	1,1-Dichloroethene	29 U	29 U	29 U	28 U	28 U	28 U	28 U	28 U	28 U	28 U	28 U	28 U
	cis-1,2-Dichloroethene	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U	6.1 U
	Tetrachloroethene	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U	1.1 U
	t-1,2-Dichloroethene	8.9 U	8.9 U	8.9 U	8.8 U	8.8 U	8.8 U	8.9 U	8.9 U	8.9 U	8.8 U	8.8 U	8.8 U
	Trichloroethene	3.2	3.9	3.9	3.2	4.3	3.9	3.9	4.3	2.8	0.71 U	0.71 U	0.71 U
	Vinyl Chloride	49 U	49 U	49 U	49 U	49 U	49 U	49 U	49 U	49 U	49 U	49 U	49 U
3M TM OVM	1,1-Dichloroethene	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U	0.99 U
	cis-1,2-Dichloroethene	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U	0.60 U
	Tetrachloroethene	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U	0.31 U
	-1,2-Dichloroethene	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U	0.63 U
	Trichloroethene	4.5	4.1	4.1	4.1	4.1	3.8	4.1	4.1	3.8	0.28 U	0.28 U	0.28 U
	Vinyl Chloride	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U	0.84 U
ATD	1,1-Dichloroethene	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U	1.0 U
	cis-1,2-Dichloroethene	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.2 U	1.2 U	1.2 U
	Tetrachloroethene	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U	1.4 U
	t-1,2-Dichloroethene	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U	1.3 U
	Trichloroethene	3.7	4.2	4.4	4.2	4.4	3.7	4	3.7	3.7	1.2 U	1.2 U	1.2 U
	Vinyl Chloride	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U	1.7 U
Radiello	1,1-Dichloroethene	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U	0.59 U
	cis-1,2-Dichloroethene	0.36	0.36	0.36 U	0.4	0.38	0.36 U	0.36 U	0.36 U	0.36	0.36 U	0.36 U	0.36 U
	Tetrachloroethene	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U	0.20 U
	t-1,2-Dichloroethene	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U	0.38 U
	Trichloroethene	4.7	4.7	4.9	4.6	4.1	3.7	3.7	4.4	4.4	0.17 U	0.17 U	0.17 U
SKC Ultra	1,1-Dichloroethene	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U	0.034 U
	cis-1,2-Dichloroethene	0.056	0.064	0.07	0.042	0.042	0.042	0.053	0.055	0.051	0.042 U	0.042 U	0.042 U
	Tetrachloroethene	0.052	0.06	0.065	0.059	0.061	0.066	0.059	0.06	0.06	0.05	0.062	0.057
	t-1,2-Dichloroethene	0.044 U	0.044 U	0.044 U	0.043 U	0.044 U	0.044 U	0.043 U	0.044 U	0.044 U	0.043 U	0.043 U	0.043 U
	Trichloroethene	1.1	1.4	1.4	1.1	0.93	1.2	1.1	1.2	1.1	0.039 U	0.039 U	0.039 U
	Vinyl Chloride	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U	0.058 U

Notes: U indicates that the compound was not detected, associated value is reporting limit. Compounds detected are in bold

Table 9. Analytical results for sub-slab (SS) measurements from OTC3.

Sub-Slab Location Sampler Type	SS-2					
	Summa	WMS	3M™ OVM	ATD	Radiello	SKC
Sample Location:	SS-2-6	SS-2-2	SS-2-5	SS-2-1	SS-2-3	SS-2-4
Client Sample ID:	SS-2-6	SS-2-2-WMS	SS-2-5-3M	SS-2-1-ATD	SS-2-3-RAD	SS-2-4-SKC
Deployment Date:	--	03/15/2010	03/15/2010	03/15/2010	03/15/2010	03/15/2010
Collection Date:	--	03/15/2010	03/15/2010	03/15/2010	03/15/2010	03/15/2010
Exposure Duration (min):	--	120	120	120	120	120
Laboratory Sample ID:	1003377B-	1003377D-	1003377F-	1003377E-	1003377C-	1003377G-
VOCs ($\mu\text{g m}^{-3}$)						
1,1-Dichloroethene	67 U	2,000 U	71 U	73 U	42 U	2.4 U
cis-1,2-Dichloroethene	13,000	1,400	130	570	26 U	57
Tetrachloroethene	110 U	78 U	22 U	100 U	14 U	3.2 U
trans-1,2-Dichloroethene	990	630 U	45 U	93 U	27 U	3.1 U
Trichloroethene	63,000	3,800	640	2,700	75	72
Vinyl Chloride	43 U	3,500 U	60 U	120 U	--	4.1 U

Sub-Slab Location Sampler Type	SS-3					
	Summa	WMS	3M™ OVM	ATD	Radiello	SKC
Sample Location:	SS-3-5	SS-3-3	SS-3-2	SS-3-3	SS-3-2	SS-3-2
Client Sample ID:	SS-3-5	SS-3-3-WMS	SS-3-2-3M	SS-3-3-ATD	SS-3-2-RAD	SS-3-2-SKC
Deployment Date:	--	10-03-15	10-03-15	10-03-15	10-03-15	10-03-15
Collection Date:	--	10-03-15	10-03-15	10-03-15	10-03-15	10-03-15
Exposure Duration (min):	--	10	10	10	10	10
Laboratory Sample ID:	1003377B-90A	1003377D-94A	1003377F-91A	1003377E-92A	1003377C-93A	1003377G-95A
VOCs ($\mu\text{g m}^{-3}$)						
1,1-Dichloroethene	640 U	24,000 U	850 U	880 U	510 U	76
cis-1,2-Dichloroethene	81,000	68,000	31,000	90,000	28,000	34,000
Tetrachloroethene	1100 U	930 U	270 U	1,200 U	170 U	130
trans-1,2-Dichloroethene	1400	7600	650	1700	740	820
Trichloroethene	560,000	340,000	180,000	360,000	130,000	53,000
Vinyl Chloride	420 U	42,000 U	720 U	1,500 U	--	50 U

Sub-Slab Location Sampler Type	SS-5					
	Summa	WMS	3M™ OVM	ATD	Radiello	SKC
Sample Location:	SS-5-6	SS-5-2	SS-5-4	SS-5-3	SS-5-5	SS-5-1
Client Sample ID:	SS-5-6	SS-5-2-WMS	SS-5-4-3M	SS-5-3-ATD	SS-5-5-RAD	SS-5-1-SKC
Deployment Date:	--	10-03-14	10-03-14	10-03-14	10-03-14	10-03-14
Collection Date:	--	10-03-15	10-03-15	10-03-15	10-03-15	10-03-15
Exposure Duration (min):	--	920	910	910	908	903
Laboratory Sample ID:	1003377B-83A	1003377D-81A	1003377F-82A	1003377E-80A	1003377C-79A	1003377G-78A
VOCs ($\mu\text{g m}^{-3}$)						
1,1-Dichloroethene	3.5 U	270 U	9.3 U	9.6 U	5.6 U	0.32 U
cis-1,2-Dichloroethene	3.5 U	57 U	5.7 U	12 U	3.4 U	0.4 U
Tetrachloroethene	6.0 U	10 U	2.9 U	13 U	1.9 U	0.43 U
trans-1,2-Dichloroethene	3.5 U	82 U	5.9 U	12 U	3.6 U	0.41 U
Trichloroethene	450	6.6 U	8.8	37	1.9	8.1
Vinyl Chloride	2.2 U	450 U	7.9 U	16 U	--	0.55 U

Notes: U means that the compound was not detected; Bold means compound detected.

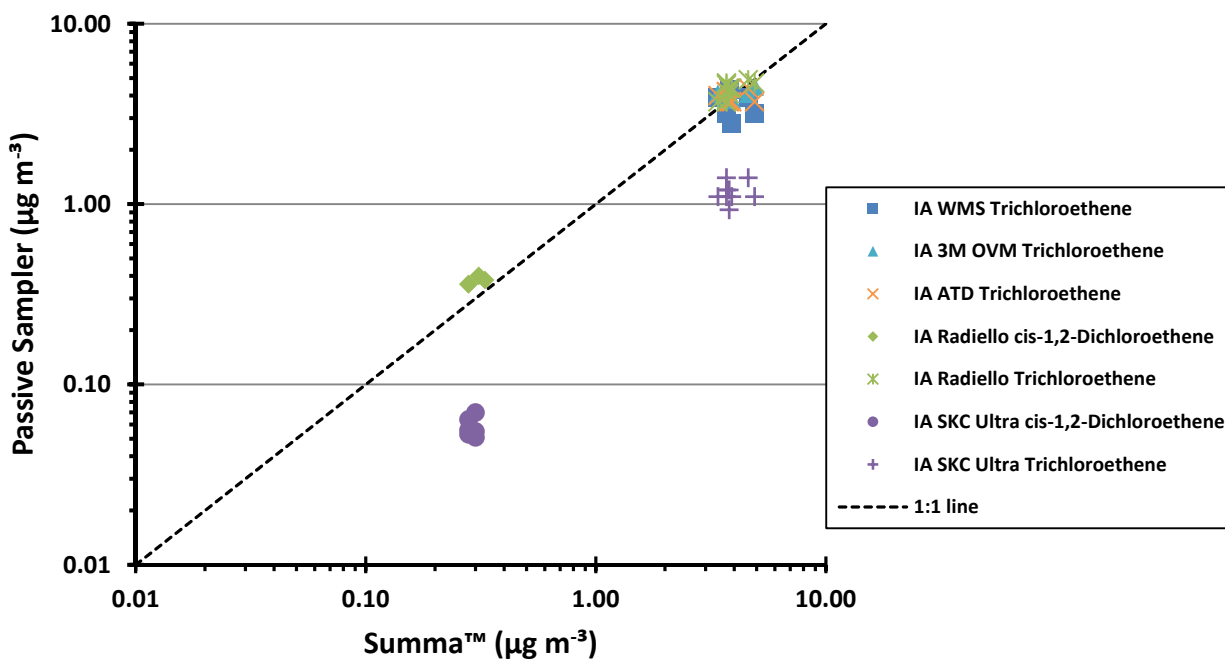


Figure 35. Correlation between VOC concentrations ($\mu\text{g m}^{-3}$) measured with passive samplers and Summa[™] canisters in indoor air from OTC3.

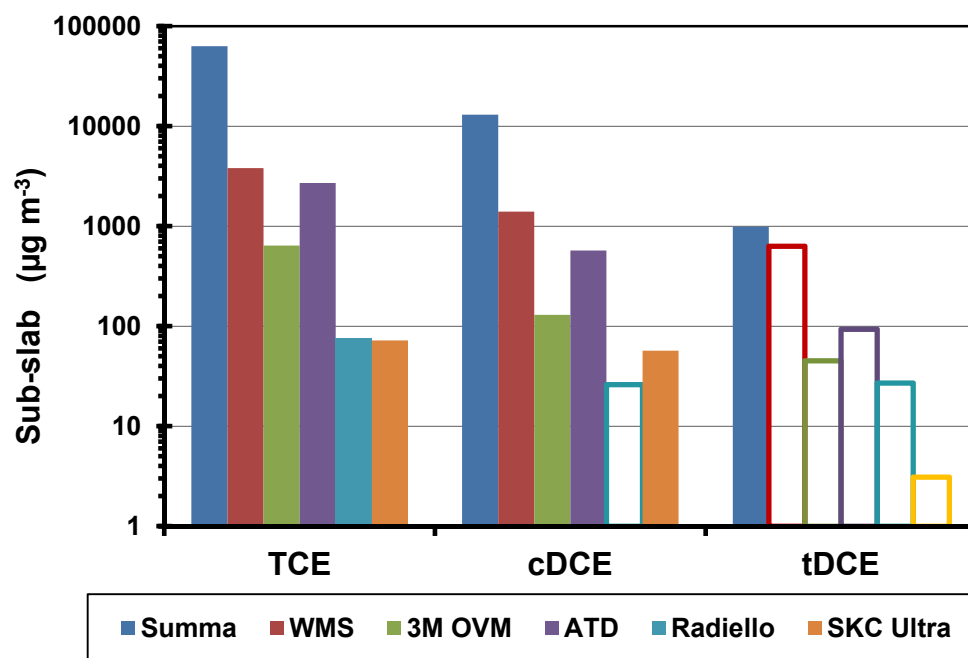


Figure 36. Sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-2 in OTC3, measured after 2 hours of fully passive sampling (empty bars represent non-detect results).

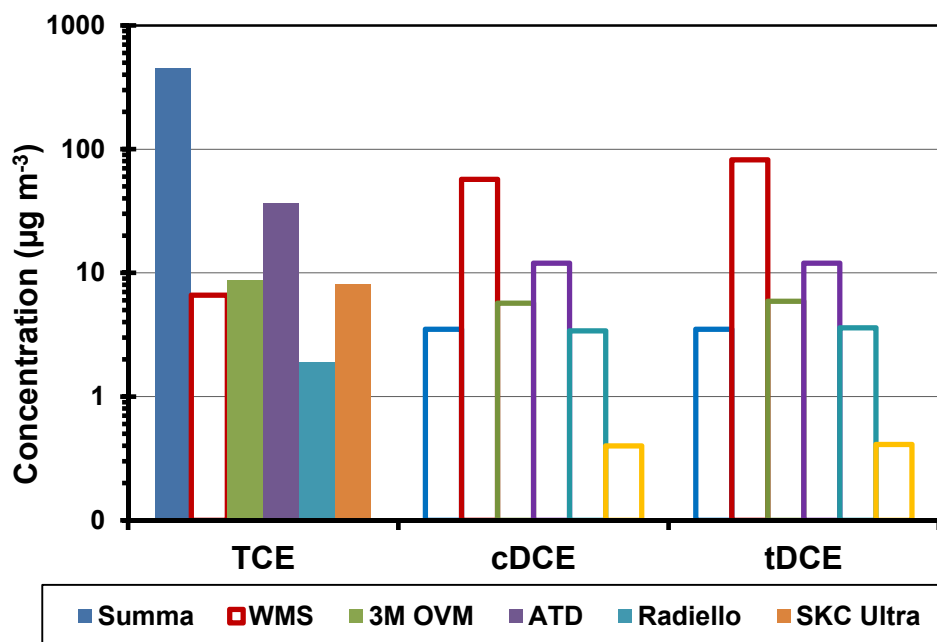


Figure 37. Sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-5 in OTC3, measured after 15 hours of fully passive sampling (empty bars represent non-detect results).

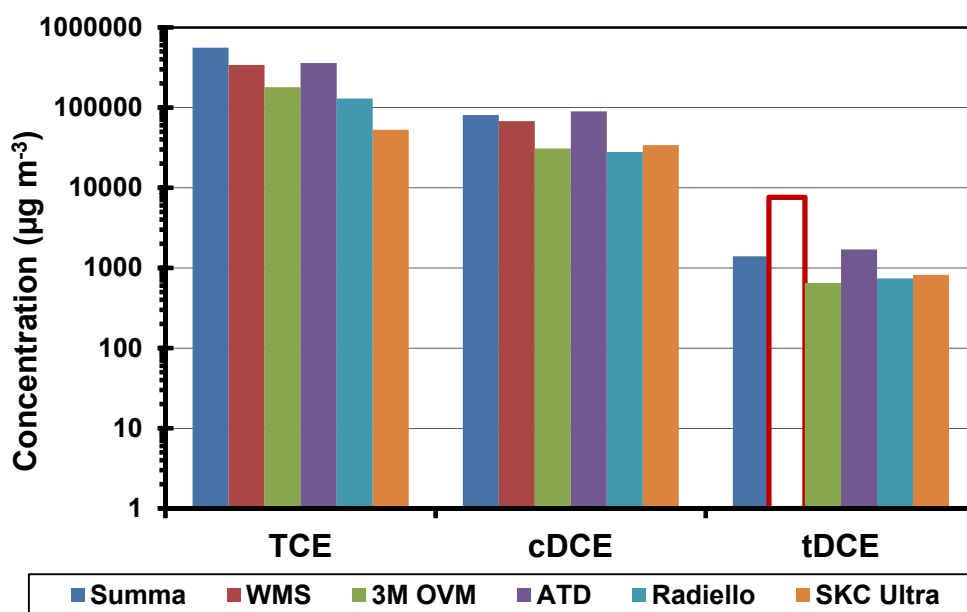


Figure 38. Semi-passive sub-slab VOC concentrations ($\mu\text{g m}^{-3}$) at location SS-3 in OTC3. These were sampled by intermittent purging with a PID unit. The data is not corrected for spatial variability in PID readings (empty bar represents non-detect results).

Table 10. Correction factors for passive samplers used at location SS-3.

Sampler	Location	PID Reading (ppmv)	Correction Factor
Summa™	SS-3-5	132	NA
3M™ OVM	SS-3-2	89	1.5
Radiello®	SS-3-2	75	1.8
SKC Ultra II	SS-3-2	85	1.6
WMS	SS-3-3	25	5.3
ATD tube	SS-3-3	37	3.6

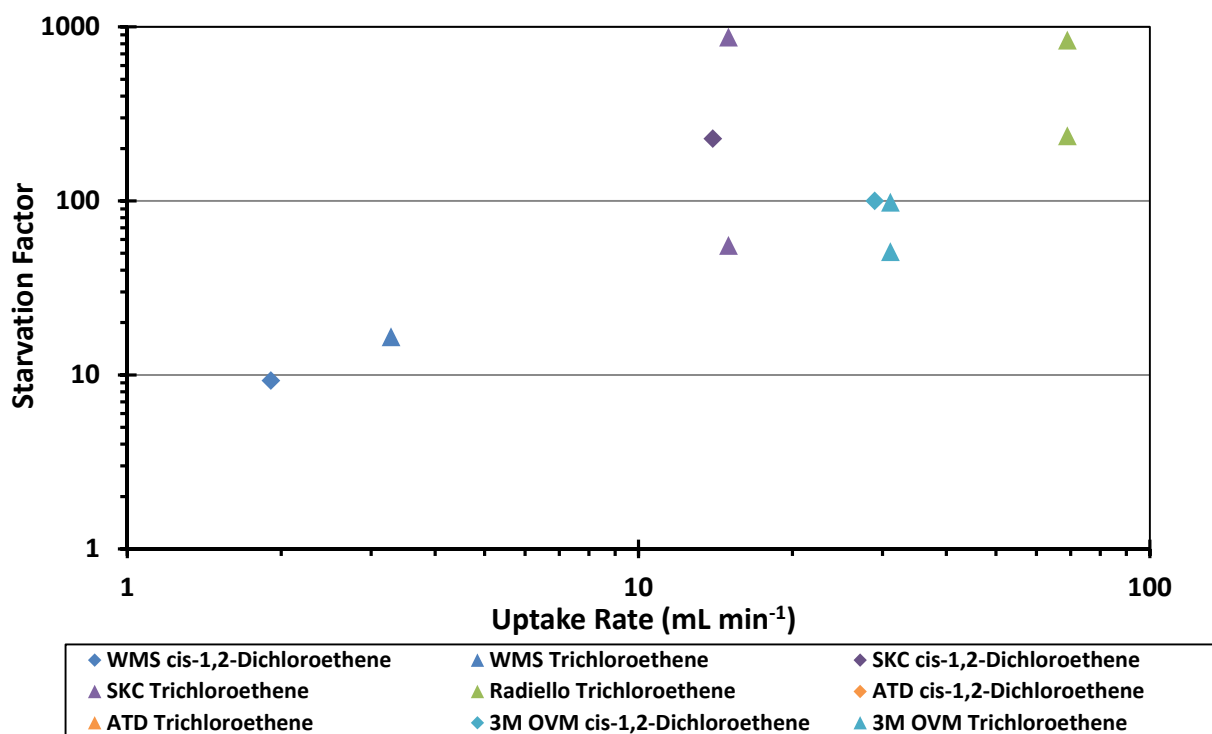


Figure 39. Starvation factor vs. uptake rate for fully passive sub-slab samples from OTC3.

6.1.1.3 Summary of OTC3 Results

A summary chart of all the indoor and sub-slab vapor data is shown in Figure 40. There is a good correlation for most of the indoor air and semi-passive sub-slab samples. The passive sub-slab samples show a negative bias from the “starvation effect” and the SKC samplers showed a negative bias compared to the other samplers, which may be attributable to poor retention by the sorbent media that were used (Chromosorb 106).

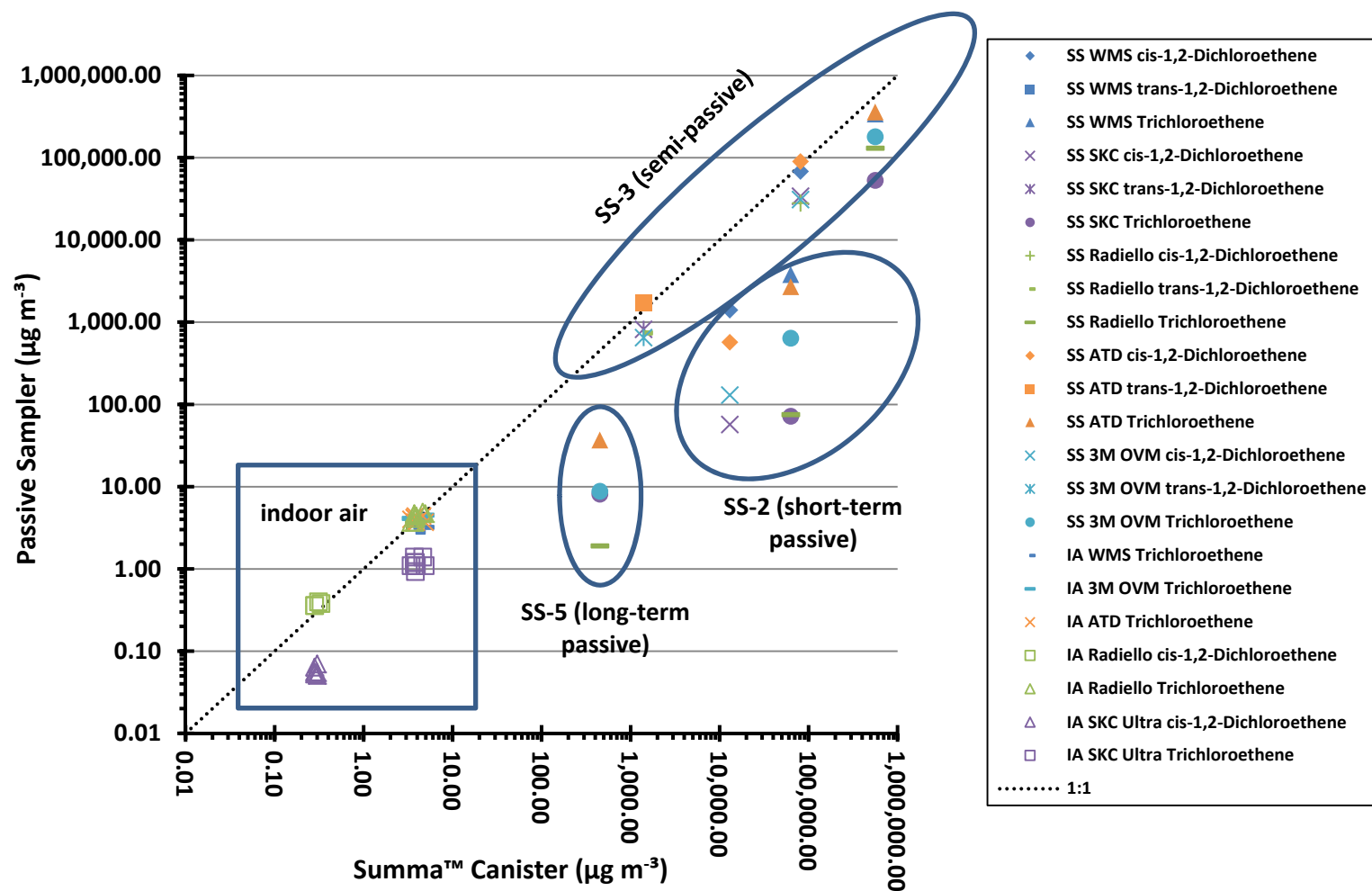


Figure 40. Comparison between passive sampler sampling approach (passive and semi-passive) to conventional Summa™ canister.

6.1.2 MCAS 137

6.1.2.1 MCAS 137 Indoor and Outdoor Air Sampling

At Cherry Point, each of the passive sampler types and the conventional active samplers (SummaTM canisters) were deployed in triplicate at each of the three indoor air sample locations in Building MCAS 137. Samplers were deployed in the break room, warehouse area, and autoclave room on 6 January 2011 and retrieved on 13 January 2011. The break room is a small room with low (8-foot) ceilings. The warehouse area was chosen as a sampling location because it is immediately outside the break room and, in contrast to the break room, is a large open area. The autoclave room was chosen as another sampling location because it is a moderately sized space, and is distant from the other two sampling locations. Outdoor air samples were collected beside a one-story shed located immediately outside MCAS 137.

The passive samplers were modified at MCAS 137 compared to the configurations used at OTC in an attempt to improve their performance. The WMS sampler was modified to increase sensitivity by using Carbopack B as the adsorbent media and thermal desorption (modified EPA Method TO-17; U.S. EPA, 1999b) for analysis. The SKC sampler was used with activated carbon instead of Chromosorb 106 to avoid the poor retention experienced with the San Diego OTC3 samples. The ATD Tube sampler was used with Carbopack B because Chromosorb 106 had shown some retention concerns for the SKC sampler at OTC3. The Radiello[®] was switched from charcoal (solvent extraction) to Carbograph 4 (thermal desorption) to enhance sensitivity. The 3MTM OVM 3500 is only available with one configuration (high uptake rates and diffusion through a plastic sheet with charcoal sorbent).

At MCAS indoor air samples (Table 11) had detectable concentrations of chlorinated VOCs and BTEX at the three sample locations. Outdoor air samples (Table 11) had detectable concentrations of VOCs, but generally at concentration less than $1 \mu\text{g m}^{-3}$. Trip blanks had detections in all five sampler types; SKC had detections for ethyl benzene ($0.048 \mu\text{g m}^{-3}$) and toluene ($0.14 \mu\text{g m}^{-3}$); 3MTM OVM had detections for 1,1-DCE ($0.45 \mu\text{g m}^{-3}$) and cis-1,2-dichloroethene ($0.22 \mu\text{g m}^{-3}$); Radiello[®] had detections for benzene ($0.051 \mu\text{g m}^{-3}$), ethyl benzene ($0.030 \mu\text{g m}^{-3}$), m,p-xylene ($0.054 \mu\text{g m}^{-3}$), o-xylene ($0.018 \mu\text{g m}^{-3}$), and toluene ($0.13 \mu\text{g m}^{-3}$); WMS had detections for benzene ($0.19 \mu\text{g m}^{-3}$), m,p-xylene ($0.05 \mu\text{g m}^{-3}$), and toluene ($0.23 \mu\text{g m}^{-3}$); and the ATD tubes had a detection of benzene ($0.93 \mu\text{g m}^{-3}$). These are all much lower than the risk-based screening levels, except for benzene in the ATD tube.

6.1.2.2 Correlation Charts for Each of the Passive Samplers

The concentrations measured at MCAS 137 with the passive samplers were plotted against the concentrations measured with the SummaTM canisters to show the correlations graphically (Figure 42). Each plot is presented using linear and logarithmic scales to show the data because the numbers span a range of almost two orders of magnitude. Where there were sufficient detections, a linear regression line was plotted, each with a fixed intercept of zero to focus on the slope and correlation coefficient. The intercept was fixed to zero because in theory the sampler should contain no detectable mass of a particular compound that is not actually present. In reality, there were some compounds detected in the trip blanks, which would cause the intercept to be different than zero in some cases. To assess the significance of the intercept on the correlation, some of the data sets were blank-corrected and re-plotted with the intercept not set to zero, but in selected comparisons, the correlation coefficient and slope were only marginally different. In contrast, the correlations between passive and active samplers were much more significantly influenced by the uptake rate, which is known to vary from compound to compound and sampler to sampler, and may also vary to a modest

degree in response to changes in temperature, humidity, wind-speed, exposure duration and concentration, among other things.

The WMS and Radiello[®] samplers had a low bias for cDCE, tDCE, 11DCA (up to one order of magnitude), and 11DCE (up to two orders of magnitude), and a slight low bias (<10×) for 12DCA. The uptake rate for these compounds is about 1 to 2 mL min⁻¹ for the WMS sampler and about 20 to 30 mL min⁻¹ for the Radiello[®]. When multiplied by the exposure time (about 7 days), this equates to an “equivalent” sample volume of 10 to 20 L for the WMS sampler and 200 to 300 liters for the Radiello[®]. The SSV for these compounds on Carbograph 4 (used in the Radiello[®]) is less than about 20 L, and the SSV for these compounds is less than 5 L with Carbopack B (used in the WMS sampler). The ATD tubes contained the same sorbent (Carbopack B) as the WMS sampler, but the uptakes rates are lower by up to a factor of 5, so the challenge volume also exceeded the SSV, but by a five-time lower amount. For the ATD tubes, cDCE, tDCE, 11DCE, and 11DCA are also biased slightly low.

The SKC and 3M[™] OVM samplers showed no significant bias for these compounds, presumably because the adsorbents used in these samplers were activated carbon, which retains VOCs more strongly than the thermally desorbable adsorbents. The MCAS 137 data show a notable improvement for the SKC Ultra Sampler, relative to the results from San Diego OTC3 where Chromasorb 106 (a weaker adsorbent) was used. This noteworthy change in the performance of the SKC sampler demonstrates the importance of careful selection of the adsorbent media for those samplers where the sorbent is interchangeable.

6.1.2.3 Summary of MCAS 137 Results

Data in Figure 41 show that the passive samplers provide very consistent and reproducible results, which in many cases are within the ±25% range of the Summa[™] canister data, and would be considered acceptable for duplicate samples with the same method and the same laboratory.

Allowing for a modest additional variability attributable to analysis by different laboratories and different methods for the different samplers, the results for most of the compounds and locations correlate well for all sampler types for PCE, TCE, and BTEX. The average relative concentration (C/C_o , where the passive sampler result is divided by the Summa[™] canister result) ranged from 0.6 to 1.6 for the five sampler types. Where the passive sampler results did not compare favorably to the Summa[™] canister results, the root cause appears to be primarily poor retention, which in hindsight could have been predicted based on a comparison of the safe sampling volume (published for active ATD tube sampling) to the equivalent sample volume (uptake rate times exposure duration for the passive samplers).

6.1.3 Naval Air Station Jacksonville

6.1.3.1 Exterior Passive Soil Gas Samples

Soil gas samples for Summa[™] canisters and all five passive samplers at NAS JAX are shown in Table 12, Table 13, and Table 14, respectively.

Table 11. Analytical results for indoor air (IA) and outdoor air (OA) at MCAS 137.

Matrix:	Indoor Air											
	Indoor Air Location #1											
	OVM			Radiello			WMS			SKC		
	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C
Exposure Time (min):	9946	9943	9943	9937	9935	9934	9913	9912	9913	9920	9921	9921
Exposure Time (days):	6.91	6.90	6.90	6.90	6.90	6.90	6.88	6.88	6.88	6.89	6.89	6.89
VOC ($\mu\text{g m}^{-3}$)												
1,1,1-Trichloroethane	6.4	6.4	8	15 E	15 E	15 E	3.3	3.4	3.7	2.8	2.8	3.4
112TCA	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U	0.069 U	0.069 U	0.069 U	0.025 U	0.025 U	0.025 U
11DCA	3.6	3.7	4	0.48	0.52	0.48	0.3	0.47	0.45	4.1	3.8	4.2
11DCE	0.81 J	0.82 J	0.94 J	0.022	0.028	0.019	0.25 U	0.36	0.25	1.4	1.5	1.4
12DCA	0.23 J	0.23 J	0.23 J	0.061	0.061	0.061	0.078 U	0.078 U	0.078 U	0.14	0.14	0.15
Benzene	0.75	0.8	0.77	0.83	0.91	0.87	0.52	0.54	0.6	1.3	1.2	1.3
cDCE	1.1	1.1	1.1	0.063	0.063	0.060	0.1	0.14	0.15	1.6	1.6	1.7
Ethyl Benzene	0.39	0.41	0.41	0.63	0.67	0.67	0.3	0.27	0.28	0.72	0.71	0.77
m,p-Xylene	1.4	1.5	1.6	2.2	2.5	2.3	1.2	1.1	1.2	2.6	2.6	2.9
o-Xylene	0.52	0.54	0.55	0.90	0.98	0.94	0.43	0.42	0.41	1	1	1.1
PCE	0.079	0.083	0.083	0.060	0.058	0.058	0.066	0.064 U	0.068	0.086	0.092	0.1
Toluene	9.2	9.8	10	9.1 E	11 E	11 E	7.5	6.9	7.5	13 E	13 E	13 E
tDCE	2.9	2.8	2.9	0.46	0.44	0.44	0.63	0.71	0.73	4.5	4.4	4.7
TCE	3.3	3.2	3.7	1.4	1.5	1.5	1.8	1.8	2	3.2	3.2	3.5

Matrix:	Indoor Air											
	Indoor Air Location #1						Indoor Air Location #2					
	ATD Tube			Summa			OVM			Radiello		
	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-1A	137-IA-1B	137-IA-1C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C
Exposure Time (min):	9920	9921	9923				10648	10647	10646	9914	9912	9909
Exposure Time (days):	6.89	6.89	6.89	--	--	--	7.39	7.39	7.39	6.88	6.88	6.88
VOC ($\mu\text{g m}^{-3}$)												
1,1,1-Trichloroethane	8.3	8.1	8.1	11	10	11	0.24 U	0.24 U	0.24 U	0.14 U	0.14 U	0.14 U
112TCA	0.46 U	0.46 U	0.46 U	0.12 U	0.18 U	0.13 U	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U
11DCA	2.6	2.4	2.0	6.2	5.8	6.1	0.23 U	0.23 U	0.23 U	0.0087 U	0.0087 U	0.0087 U
11DCE	0.90	0.94	1.2	2.4	2.1	2.2	0.45 J	0.45 J	0.45 J	0.0026 U	0.0026 U	0.0026 U
12DCA	0.40 U	0.40 U	0.40 U	0.21	0.21	0.19	0.23 J	0.23 J	0.23 J	0.012	0.013	0.014
Benzene	1.6	1.8	1.6	0.76	0.70	0.67	0.94	0.9	0.86	0.91	0.98	0.91
cDCE	1.2	1.1	1.2	1.8	1.7	1.7	0.024	0.025	0.023	0.0031 U	0.0031 U	0.0031 U
Ethyl Benzene	0.84	0.84	0.97	0.62 U	0.91 U	0.64 U	0.45	0.53	0.5	0.78	0.79	0.75
m,p-Xylene	3.0	3.0	3.7	1.9	1.7	1.8	1.2	1.4	1.3	2.1	2.1	2.0
o-Xylene	1.2	1.1	1.4	0.70	0.91 U	0.68	0.47	0.54	0.51	0.86	0.90	0.86
PCE	0.84 U	0.84 U	0.84 U	0.13	0.18 U	0.13 U	0.18	0.2	0.19	0.15	0.15	0.14
Toluene	23	22	23	16	15	15	3.3	3.7	3.5	4.7 E	4.7 E	4.4 E
tDCE	3.2	3.2	3.4	4.2	4.2	4.1	29	32	31	2.3 E	2.5 E	2.9 E
TCE	4.4	4.4	4.6	4.9	4.8	4.7	0.025	0.024	0.026	0.0073	0.0094	0.0088

Table 11. Analytical results for indoor air (IA) and outdoor air (OA) at MCAS 137. (Continued)

Matrix:	Indoor Air											
	Indoor Air Location #2											
	WMS			SKC			ATD Tube			Summa		
	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C	137-IA-2A	137-IA-2B	137-IA-2C
Exposure Time (min):	9912	9913	9914	9905	9904	9904	9912	9914	9912			
Exposure Time (days):	6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88	--	--	--
VOC ($\mu\text{g m}^{-3}$)												
1,1,1-Trichloroethane	0.18 U	0.18 U	0.18 U	0.029 U	0.029 U	0.029 U	0.54 U	0.54 U	0.54 U	0.15 U	0.14 U	0.18 U
112TCA	0.069 U	0.069 U	0.069 U	0.025 U	0.025 U	0.025 U	0.46 U	0.46 U	0.46 U	0.15 U	0.14 U	0.18 U
11DCA	0.17 U	0.17 U	0.17 U	0.015 U	0.015 U	0.015 U	0.40 U	0.40 U	0.40 U	0.15 U	0.14 U	0.18 U
11DCE	0.25 U	0.25 U	0.25 U	0.037	0.036	0.024	0.35 U	0.35 U	0.35 U	0.15 U	0.14 U	0.18 U
12DCA	0.078 U	0.078 U	0.078 U	0.056	0.057	0.054	0.40 U	0.40 U	0.40 U	0.15 U	0.14 U	0.18 U
Benzene	0.59	0.61	0.61	1.8	1.8	1.6	1.8	1.8	1.6	0.88	0.85	0.87
cDCE	0.1 U	0.1 U	0.1 U	0.16	0.16	0.16	0.43 U	0.43 U	0.43 U	0.15 U	0.14 U	0.18 U
Ethyl Benzene	0.34	0.32	0.29	0.87	0.9	0.84	0.98	1.0	1.0	0.76 U	0.70 U	0.92 U
m,p-Xylene	1.1	1	0.93	2.6	2.7	2.5	2.8	2.8	2.8	1.7	1.7	1.7
o-Xylene	0.38	0.36	0.34	1	1.1	0.96	1.1	1.1	1.1	0.76 U	0.70 U	0.92 U
PCE	0.14	0.13	0.13	0.24	0.25	0.22	0.84 U	0.84 U	0.84 U	0.28	0.28	0.26
Toluene	3.4	3.2	2.7	6.4	6.5	6.1	7.9	7.9	8.2	5.6	5.4	5.7
tDCE	3.3	5.3	6.2	28 E	29 E	28 E	32	29	29	47	49	49
TCE	0.083 U	0.083 U	0.083 U	0.035	0.031	0.026	0.54 U	0.54 U	0.54 U	0.15 U	0.14 U	0.18 U

Matrix:	Indoor Air											
	Indoor Air Location #3											
	OVM			Radiello			WMS			SKC		
	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C
Exposure Time (min):	10744	10745	10738	10007	10004	10005	9974	9976	9973	9996	9999	9997
Exposure Time (days):	7.46	7.46	7.46	6.95	6.95	6.95	6.93	6.93	6.93	6.94	6.94	6.94
VOC ($\mu\text{g m}^{-3}$)												
1,1,1-Trichloroethane	0.24 U	0.24 U	0.24 U	0.13 U	0.13 U	0.13 U	0.18 U	0.18 U	0.18 U	0.029 U	0.029 U	0.029 U
112TCA	0.25 U	0.25 U	0.25 U	0.027 U	0.027 U	0.027 U	0.069 U	0.069 U	0.069 U	0.024 U	0.024 U	0.024 U
11DCA	0.22 U	0.22 U	0.22 U	0.0086 U	0.0086 U	0.0086 U	0.17 U	0.17 U	0.17 U	0.015 U	0.015 U	0.015 U
11DCE	0.45 J	0.45 J	0.45 J	0.0025 U	0.0025 U	0.0025 U	0.24 U	0.24 U	0.24 U	0.02 U	0.022	0.024
12DCA	0.22 J	0.22 J	0.22 J	0.016	0.020	0.018	0.078 U	0.078 U	0.078 U	0.054	0.058	0.053
Benzene	1	1.1	1.2	1.0	1.0	1.0	0.61	0.66	0.66	1.6	1.6	1.5
cDCE	0.027	0.021 U	0.024	0.0031 U	0.0031 U	0.0031 U	0.1 U	0.1 U	0.1 U	0.14	0.14	0.13
Ethyl Benzene	0.5	0.45	0.52	0.70	0.62	0.66	0.32	0.31	0.27	0.74	0.81	0.79
m,p-Xylene	1.4	1.2	1.4	1.8	1.6	1.7	0.96	0.94	0.83	2.1	2.3	2.2
o-Xylene	0.52	0.48	0.38	0.77	0.69	0.77	0.36	0.37	0.32	0.87	0.93	0.88
PCE	0.2	0.16	0.19	0.13	0.11	0.12	0.12	0.13	0.11	0.18	0.2	0.18
Toluene	4	3.7	4.2	4.7 E	4.3 E	4.7 E	2.5	2.6	2.4	5.9	6.4	6.1
tDCE	30	26	35	2.4 E	3.6 E	2.8 E	1.7	2.5	1.9	26 E	27 E	26 E
TCE	0.024	0.024 U	0.026	0.0067	0.0077	0.0072	0.082 U	0.082 U	0.082 U	0.024 U	0.024 U	0.024 U

Table 11. Analytical results for indoor air (IA) and outdoor air (OA) at MCAS 137. (Continued)

Matrix: Sample Location: Sampler Type: Sample Location: Exposure Time (min): Exposure Time (days): VOC ($\mu\text{g m}^{-3}$)	Indoor Air						Outdoor Air						
	Indoor Air Location #3						Outdoor Air						
	ATD Tube			Summa			OVM		Radiello	WMS	SKC	ATD Tube	Summa
	137-IA-3A	137-IA-3B	137-IA-3C	137-IA-3A	137-IA-3B	137-IA-3C	137-OA-1	137-OA-1-OVM Lab Dup	137-OA-1	137-OA-1	137-OA-1	137-OA-1	137-OA-1
	9995	9993	9993				9931	9931	9927	9921	9924	9935	
	6.94	6.94	6.94	--	--	--	6.90	6.90	6.89	6.89	6.89	6.90	--
1,1,1-Trichloroethane	0.54 U	0.54 U	0.54 U	0.14 U	0.13 U	0.14 U	0.24 U	0.24 U	0.14 U	0.18 U	0.019 U	0.54 U	0.14 U
112TCA	0.46 U	0.46 U	0.46 U	0.14 U	0.13 U	0.14 U	0.25 U	0.25 U	0.027 U	0.069 U	0.018 U	0.46 U	0.14 U
11DCA	0.40 U	0.40 U	0.40 U	0.14 U	0.13 U	0.14 U	0.23 U	0.23 U	0.0087 U	0.17 U	0.016 U	0.40 U	0.14 U
11DCE	0.35 U	0.35 U	0.35 U	0.14 U	0.13 U	0.14 U	0.45 J	0.45 J	0.0026 U	0.24 U	0.024	0.35 U	0.14 U
12DCA	0.40 U	0.40 U	0.40 U	0.14 U	0.13 U	0.14 U	0.23 J	0.23 J	0.065	0.078 U	0.021	0.40 U	0.14 U
Benzene	1.7	2.3	1.7	0.88	0.88	0.88	0.77	0.82	0.83	0.6	0.77	1.2	1.0
cDCE	0.43 U	0.43 U	0.43 U	0.14 U	0.13 U	0.14 U	0.021 U	0.021 U	0.0031 U	0.1 U	0.014	0.43 U	0.14 U
Ethyl Benzene	0.80	0.90	0.87	0.70 U	0.65 U	0.70 U	0.28 U	0.28 U	0.17	0.12	0.14	0.74 U	0.69 U
m,p-Xylene	2.1	2.4	2.3	1.4	1.2	1.4	0.28 U	0.28 U	0.42	0.35	0.33	0.74 U	0.69 U
o-Xylene	0.93	1.1	1.0	0.70 U	0.65 U	0.70 U	0.28 U	0.28 U	0.17	0.13	0.15	0.74 U	0.69 U
PCE	0.83 U	0.83 U	0.83 U	0.21	0.23	0.25	0.082	0.083	0.055	0.085	0.072	0.83 U	0.14 U
Toluene	7.5	8.4	7.8	4.9	5.2	5.2	0.85	0.87	1.1	0.81	0.9	1.8	1.5
tDCE	27	27	27	39	37	38	0.43 U	0.43 U	0.041	0.15 U	0.19	0.45 U	0.18
TCE	0.54 U	0.54 U	0.54 U	0.14 U	0.13 U	0.14 U	0.024 U	0.024 U	0.0064	0.083 U	0.018 U	0.54 U	0.14 U

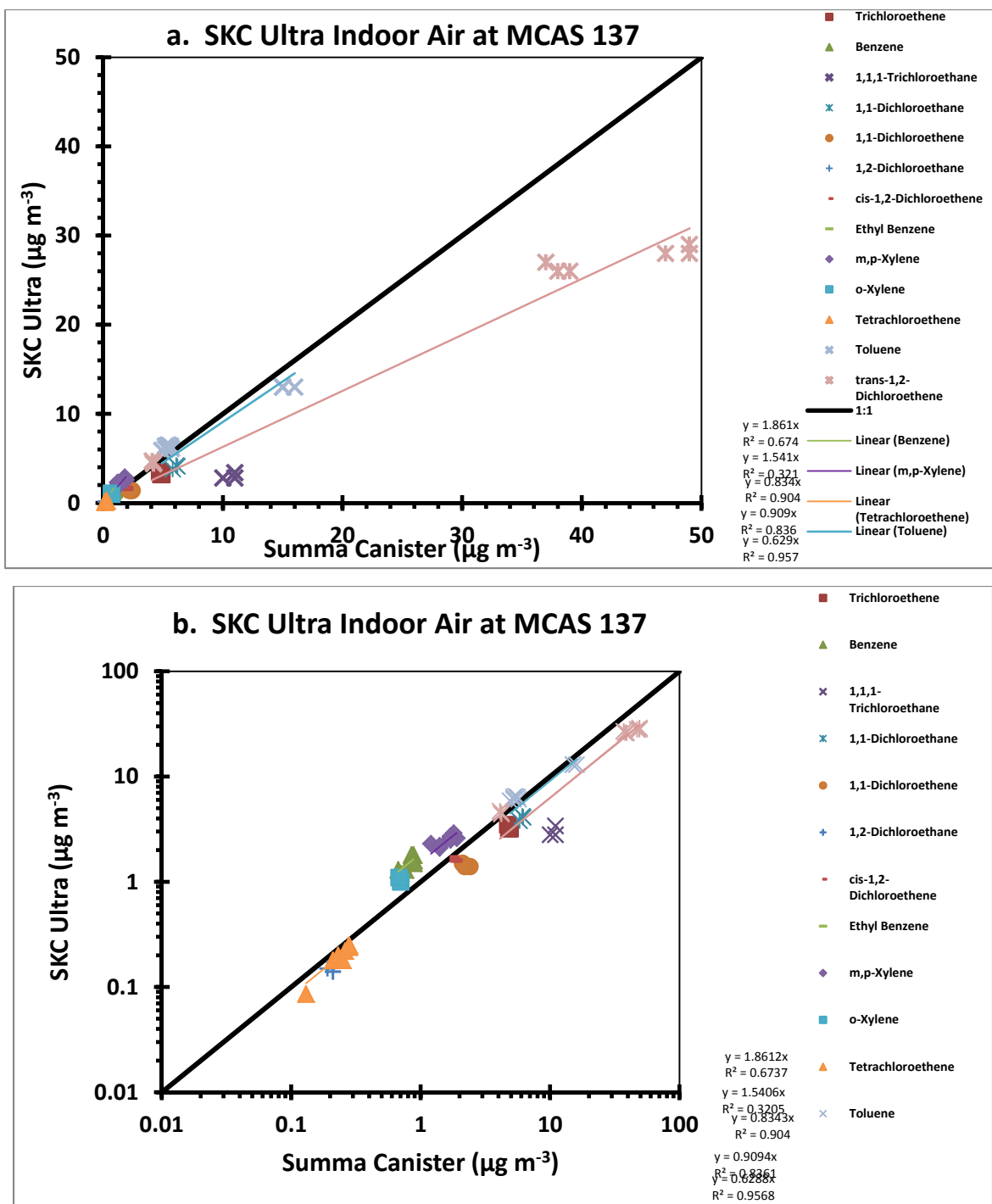


Figure 41. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. Two plots are presented for each passive sampler to show both the complete range of concentrations (log-log plot) and a close up of the lowest concentration range: SKC Ultra a, b; Radiello® c, d; ATD e, f; 3M™ OVM g, and h; WMS i, j.

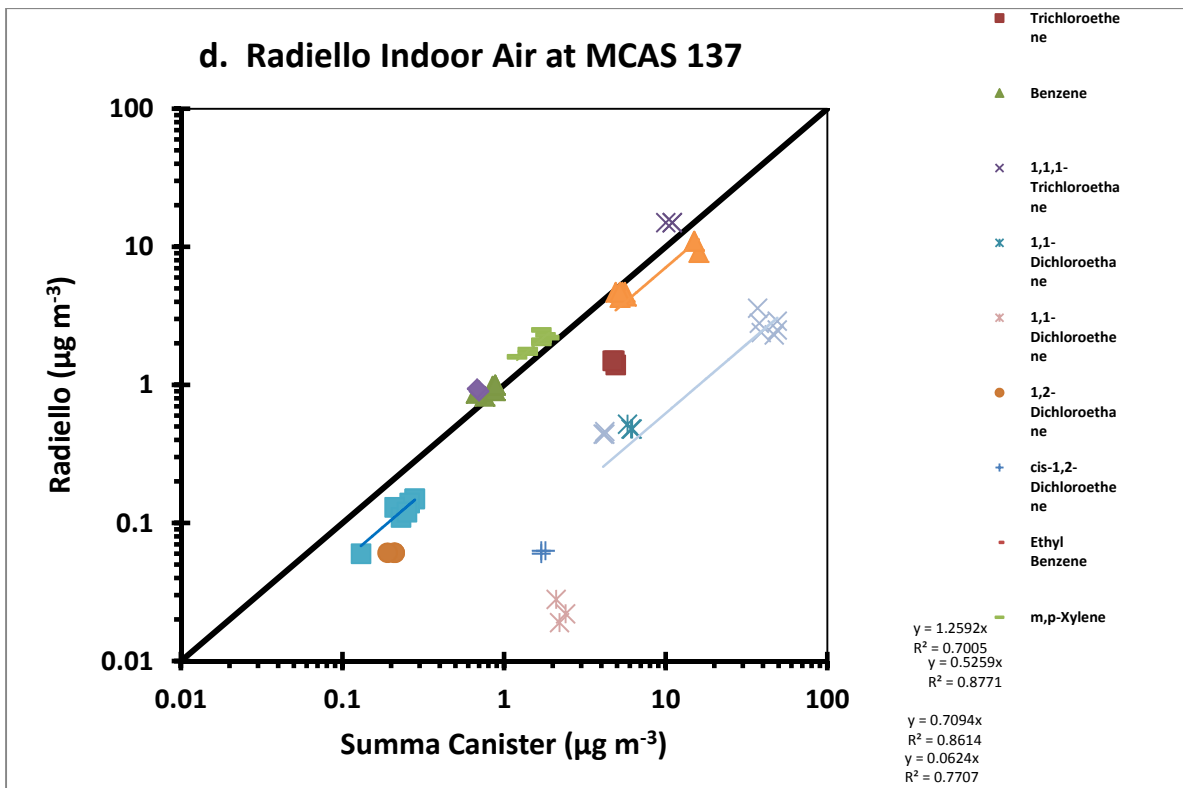
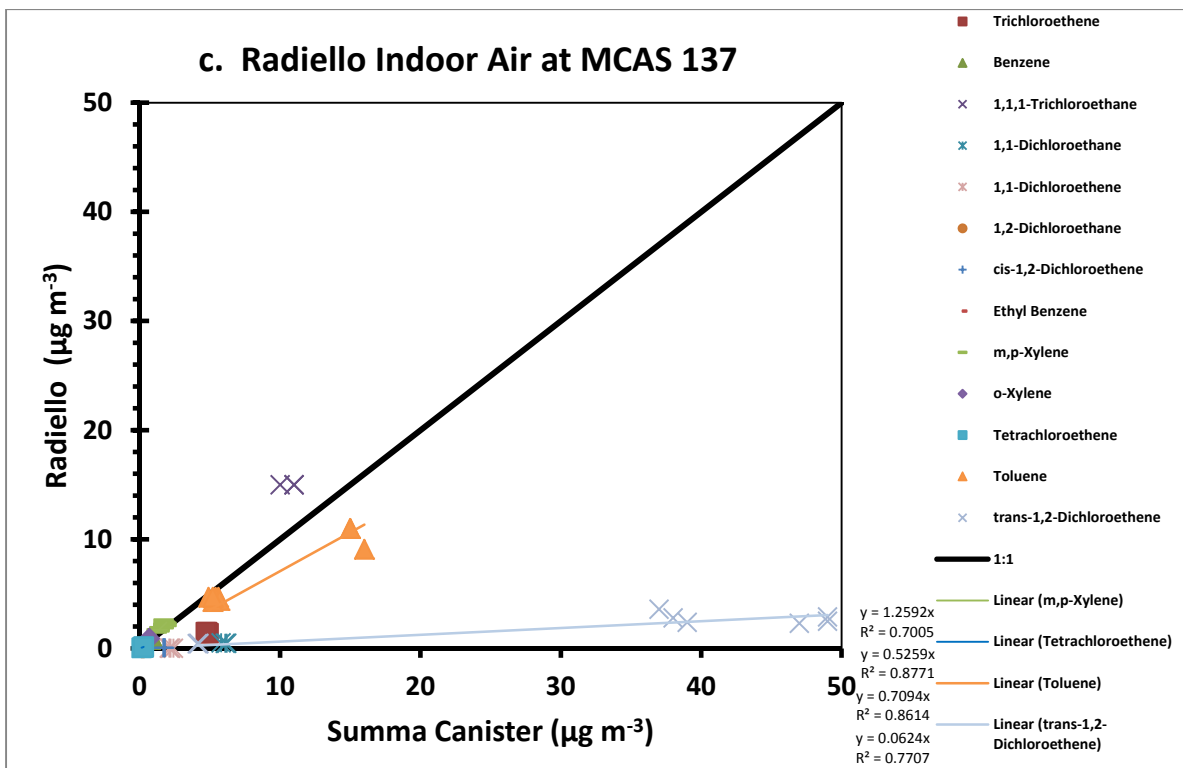


Figure 41. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. (Continued)

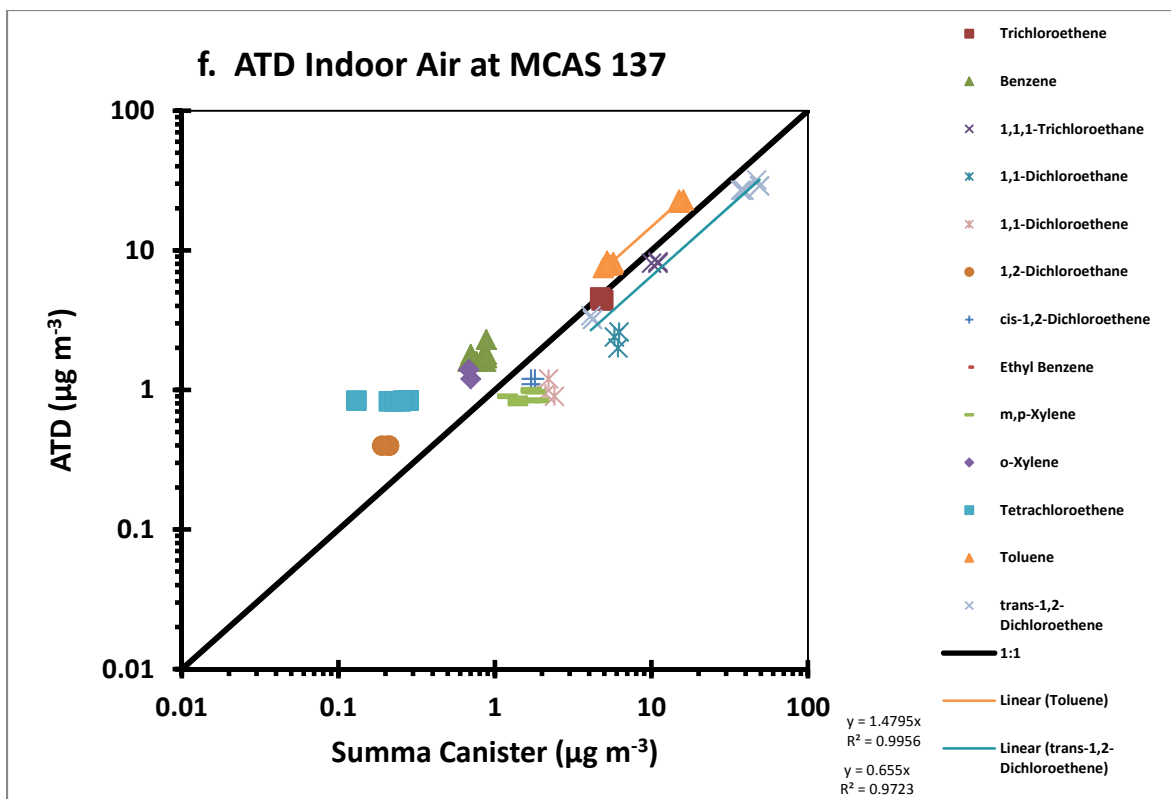
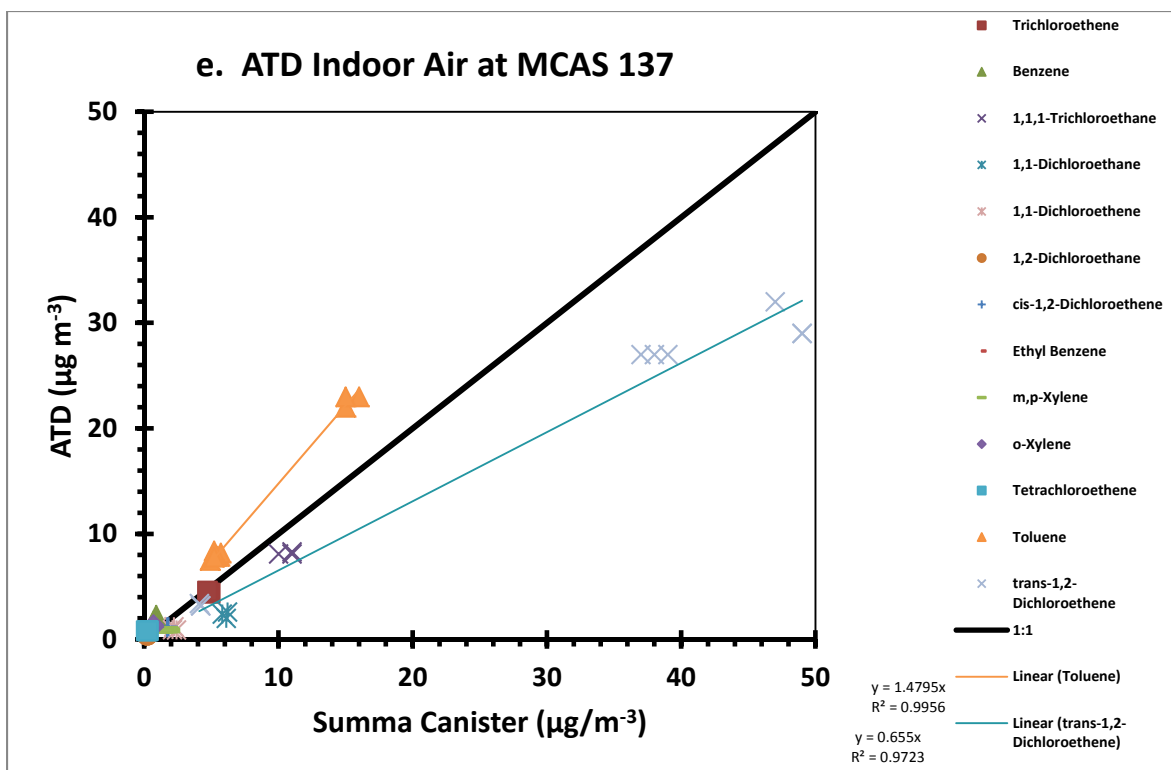


Figure 41. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. (Continued)

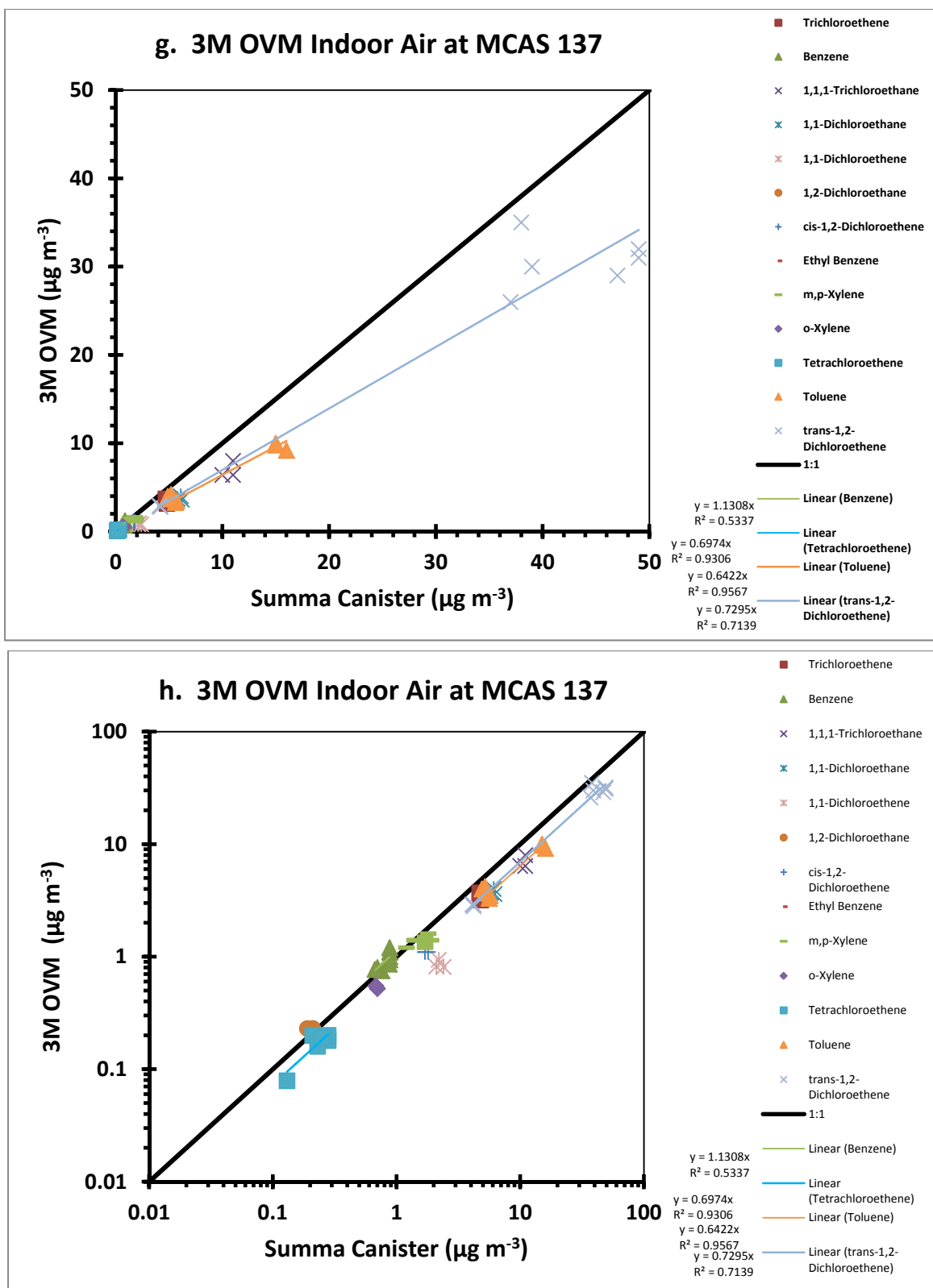


Figure 41. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. (Continued)

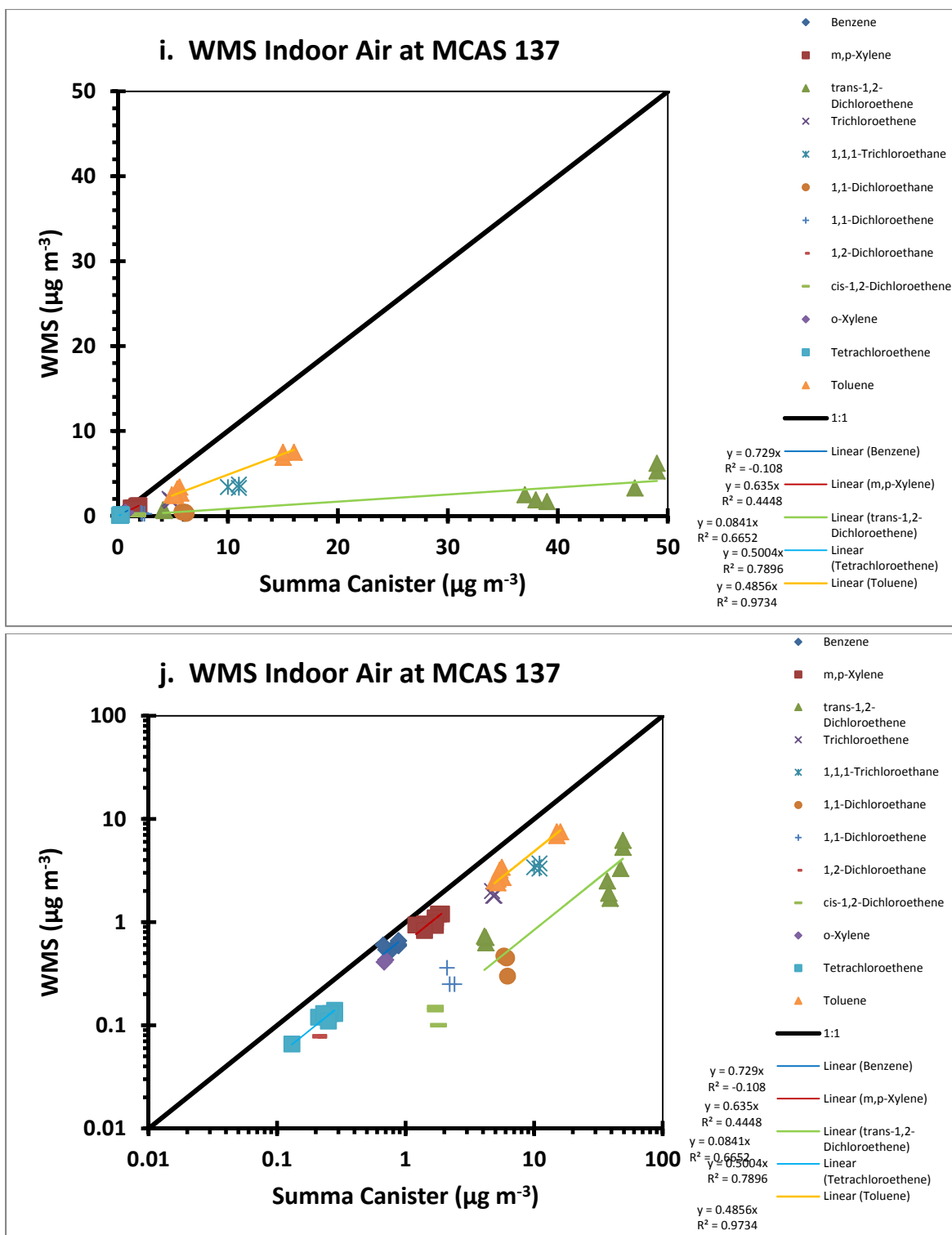


Figure 42. Comparison of the VOC concentrations measured in indoor air with each passive sampler to those measured with conventional Summa™ canister at MCAS 137. (Continued)

Table 12. Analytical results for soil gas and sub-slab VOCs sampled with conventional Summa™ canisters at NAS JAX.

Sample ID	Date	Time	Trichloroethene		Tetrachloroethene		cis-1,2-Dichloroethene		trans-1,2-Dichloroethene	
			µg m ⁻³	ppbV	µg m ⁻³	ppbV	µg m ⁻³	ppbV	µg m ⁻³	ppbV
SG-FP-20-1-RAD-SUM	12-Jan-11	8:33 AM	170	32	480	72	2,000	490	580	150
SG-FP-20-1-SKCPH-SUM	12-Jan-11	11:50 AM	200	37	730	110	1,800	450	520	130
SG-FP-60-1-OVM-SUM	11-Jan-11	4:29 PM	160	30	480	70	1,600	420	520	130
SG-FP-20-1-ATD-SUM	12-Jan-11	9:38 AM	180	34	560	83	1,700	440	520	130
SG-FP-60-1-SKCPH-SUM	12-Jan-11	1:14 PM	190	36	700	100	1,800	440	500	130
SG-FP-20-1-OVM-SUM	12-Jan-11	9:59 AM	180	34	560	83	1,600	410	480	120
SG-FP-60-1-WMSPH-SUM	12-Jan-11	10:20 AM	170	32	550	81	1,500	370	410	100
SG-FP-60-1-ATD-SUM	12-Jan-11	11:22 AM	170	31	560	82	1,400	360	390	98
SG-FP-20-1-WMSPH-SUM	12-Jan-11	12:32 PM	190	35	690	100	1,700	430	500	130
SG-FP-60-1-RAD-SUM	12-Jan-11	2:15 PM	190	35	650	95	1,800	460	520	130
SG-FP-40-2-SKCPH-A-SUM	12-Jan-11	12:15 PM	230	43	920	140	2,100	520	510	130
SG-FP-40-2-RAD-A-SUM	11-Jan-11	3:56 PM	210	40	720	110	2,400	590	580	150
SG-FP-40-2-ATD-A-SUM	11-Jan-11	3:15 PM	180	34	590	87	2,100	520	490	120
SG-FP-40-2-OVM-A-SUM	11-Jan-11	2:34 PM	220	41	760	110	2,300	580	560	140
SG-FP-40-2-RAD-B-SUM	11-Jan-11	4:38 PM	200	38	690	100	2,300	580	540	140
SG-FP-40-2-WMSPH-A-SUM	12-Jan-11	9:26 AM	250	47	950	140	2,900	740	650	160
SG-FP-40-2-OVM-B-SUM	12-Jan-11	8:40 AM	290	54	990	150	3,900	980	800	200
SG-FP-40-2-WMSPH-B-SUM	12-Jan-11	10:09 AM	290	53	1,300	190	2,600	670	720	180
SG-FP-40-2-ATD-B-SUM	12-Jan-11	10:52 AM	260	48	1,000	150	2,700	690	620	160
SG-FP-40-2-OVM-C-SUM	12-Jan-11	11:34 AM	250	47	1,000	150	2,600	660	600	150
SG-FP-40-2-ATD-C-SUM	12-Jan-11	1:03 PM	230	43	940	140	2,500	620	540	140
SG-FP-40-2-WMSPH-C-SUM	12-Jan-11	1:46 PM	230	43	930	140	2,400	600	540	140
SG-FP-40-2-SKCPH-B-SUM	12-Jan-11	2:28 PM	250	46	1,000	150	2,500	640	580	150
SG-FP-40-2-SKCPH-C-SUM	12-Jan-11	3:13 PM	230	44	990	150	2,400	600	550	140
SG-FP-40-2-RAD-C-SUM	12-Jan-11	3:53 PM	220	42	940	140	2,400	590	530	130
SG-FP-20-3-RAD-SUM	12-Jan-11	12:02 PM	220	40	790	120	2,200	550	650	160
SG-FP-60-3-OVM-SUM	12-Jan-11	12:22 PM	170	33	630	94	1,800	440	520	130
SG-FP-60-3-RAD-SUM	12-Jan-11	1:31 PM	160	30	610	90	1,600	400	460	120
SG-FP-60-3-WMSPH-SUM	12-Jan-11	2:39 PM	140	25	520	77	1,300	320	380	95
SG-FP-60-3-SKCPH-SUM	12-Jan-11	3:37 PM	140	27	550	82	1,300	340	390	99
SG-FP-20-3-ATD-SUM	12-Jan-11	4:41 PM	140	26	530	78	1,300	330	380	97
SG-FP-20-3-WMSPH-SUM	12-Jan-11	5:02 PM	140	25	520	77	1,300	320	370	94
SG-FP-20-3-OVM-SUM	12-Jan-11	5:24 PM	130	25	540	79	1,200	310	360	91
SG-FP-20-3-SKCPH-SUM	12-Jan-11	5:45 PM	130	24	520	77	1,200	300	340	87
SG-FP-60-3-ATD-SUM	12-Jan-11	6:08 PM	130	24	520	77	1,200	300	340	86
SSP-4-SUM (sub-slab)			960	180	7,400	1,100	3,800	950	2,300	580
SSP-5-SUM (sub-slab)			1,900	350	17,000	2,400	440	1,100	4,900	1,200
SSP-6-SUM (sub-slab)			3,400	360	18,000	2,600	14,000	3,400	19,000	4,800

Table 13. Analytical results for passive soil gas samples at NAS JAX.

Sampler Type (Subtype/Sorbent)	Sample ID	Void Space Under Sampler	Exposure Time (min)	cis-1,2-Dichloroethene		Tetrachloroethene		trans-1,2-Dichloroethene		Trichloroethene	
				Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)
3M™ OVM (Regular/ charcoal)	SG-FP-20-1-OVM	6"	20	800	1,136	240	424	270	384	90	145
	SG-FP-20-3-OVM	18"	20	750	1,065	270	477	270	384	94	151
	SG-FP-40-2-OVM-A	12"	40	2,400	1,705	680	601	690	490	230	185
	SG-FP-40-2-OVM-B	12"	40	3,200	2,273	820	724	900	639	270	217
	SG-FP-40-2-OVM-C	12"	40	2,400	1,705	780	689	730	518	240	193
	SG-FP-60-1-OVM	6"	60	2,100	994	470	277	700	331	190	102
	SG-FP-60-3-OVM	18"	60	2,700	1,278	880	518	990	469	310	166
ATD Tube (Regular/ Carbopack B)	SG-FP-20-1-ATD	6"	20	22	2,157	8.4	1,024	6.5	637	3.1	310
	SG-FP-20-3-ATD	18"	20	20	1,961	7.4	902	6.4	627	2.7 U	270 U
	SG-FP-40-2-ATD-A	12"	40	77	3,775	18	1,098	17	833	5.6	280
	SG-FP-40-2-ATD-B	12"	40	69	3,382	25	1,524	17	833	6.8	340
	SG-FP-40-2-ATD-C	12"	40	67	3,284	26	1,585	16	784	6.6	330
	SG-FP-60-1-ATD	6"	60	76	2,484	24	976	20	654	7.5	250
	SG-FP-60-3-ATD	18"	60	52	1,699	22	894	16	523	6.1	203
WMS (Amber pinhole/ Anasorb 747)	SG-FP-20-1-WMSPH	6"	20	19	1,806	15	670	100 U	9,823 U	5.0 U	162 U
	SG-FP-20-3-WMSPH	18"	20	16	1,521	13	580	100 U	9,823 U	6.7	380
	SG-FP-40-2-WMSPH-A	12"	40	82	3,897	45	1,004	100 U	4,912 U	12	340
	SG-FP-40-2-WMSPH-B	12"	40	58	2,757	48	1,071	100 U	4,912 U	12	340
	SG-FP-40-2-WMSPH-C	12"	40	58	2,757	47	1,049	100 U	4,912 U	11	312
	SG-FP-60-1-WMSPH	6"	60	52	1,648	38	565	100 U	3,274 U	12	227
	SG-FP-60-3-WMSPH	18"	60	49	1,553	42	625	100 U	3,274 U	14	265
Radiello (Yellow bodies/ charcoal)	SG-FP-20-1-RAD	6"	20	1,090	1,730	150 U	295 U	300 U	476 U	200 U	369 U
	SG-FP-20-3-RAD	18"	20	770	1,222	150 U	295 U	300 U	476 U	200 U	369 U
	SG-FP-40-2-RAD-A	12"	40	3,520	2,794	150 U	148 U	300 U	238 U	200 U	185 U
	SG-FP-40-2-RAD-B	12"	40	2,700	2,143	230	226	370	294	200 U	185 U
	SG-FP-40-2-RAD-C	12"	40	3,090	2,452	320	315	390	310	200 U	185 U
	SG-FP-60-1-RAD	6"	60	3,460	1,831	105 U	98 U	520	275	200 U	123 U
	SG-FP-60-3-RAD	18"	60	2,990	1,582	530	348	580	307	200 U	123 U
SKC* (12-hole cap, Carbograph 5)	SG-FP-20-1-SKCPH	6"	20	32.5	2,704	11.4	1,040	9.2	770	*	*
	SG-FP-20-3-SKCPH	18"	20	25.6	2,129	7.1	648	7.6	634	4.7	407
	SG-FP-40-2-SKCPH-A	12"	40	90.2	3,758	19.3	875	19.3	806	12.7	546
	SG-FP-40-2-SKCPH-B	12"	40	80.5	3,356	22.5	1,023	19.5	811	1.5	64
	SG-FP-40-2-SKCPH-C	12"	40	77.7	3,236	20.2	920	17.9	747	3.2	139
	SG-FP-60-1-SKCPH	6"	60	97.0	2,693	19.9	603	24.3	675	14.3	410
	SG-FP-60-3-SKCPH	18"	60	96.6	2,683	18.4	558	26.4	734	19.9	572
	SKC Trip Blank	--	--	< 5	--	--	--	< 5	--	23.4	--

* - The SKC trip blank contained a significant level of TCE (23.4 ng); this mass was subtracted from the sample masses. Sample SG-FP-20-1-SKCPH had less than 23.4 ng TCE on it.

Table 14. Analytical results for passive sub-slab samples at NAS JAX.

Sampler Type (Subtype/Sorbent)	Sample ID	cis-1,2-Dichloroethene		Tetrachloroethene		trans-1,2-Dichloroethene		Trichloroethene	
		Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)	Mass (ng)	Concentration ($\mu\text{g m}^{-3}$)
ATD tube (pin-hole/Carbopack B)	SSP-4-ATD	18	5,998	32	13,140	12	3,999	4.6	1,549
	SSP-5-ATD	22	7,331	69	28,332	25	8,331	9	3,030
	SSP-6-ATD	64	21,328	120	49,273	88	29,326	21	7,071
WMS (amber pin-hole/Anasorb 747)	SSP-4-WMSPH	150	4,753	550	8,185	100 U	2,679 U	60	1,134
	SSP-5-WMSPH	150	4,753	1200	17,857	170	5,566	110	2,079
	SSP-6-WMSPH	590	18,695	1800	26,786	900	29,470	260	4,913
Radiello [®] (yellow body/charcoal)	SSP-4-RAD	4220	2,233	2820	1,850	2540	1,344	530	326
	SSP-5-RAD	5330	2,820	7270	4,770	5580	2,952	1990	1,224
	SSP-6-RAD	19740	10,444	9960	6,535	25010	13,233	4260	2,620

Figure 42 shows the correlation between the passive soil gas samples and the Summa™ canisters. An ideal correlation would have a slope of 1 and an intercept of zero with a correlation coefficient (R^2) of 1.00. The passive samplers all yielded regression lines with a slope very similar to the 1:1 line and R^2 values of 0.80 to 0.96. The WMS and Radiello® samplers have regression lines that fall within $\pm 25\%$ of the ideal 1:1 correlation line, and the WMS sampler has a better correlation coefficient (0.96 compared to 0.80 for the Radiello®). All five passive samplers have correlation lines that fall within $\pm 50\%$ of the ideal correlation (inner dotted lines). Only seven of the 117 detectable results fell outside the $\pm 2\times$ error bars (outer dashed lines). The SKC trip blank contained PCE (0.0234 μg), which may help to explain four of the results outside the $\pm 2\times$ range. All other samplers had non-detect results for their trip blanks.

Data from the three passive probes with 6-, 12-, and 18-inch long void spaces were evaluated to assess whether there was any appreciable difference between the probe designs. For each sample, the measured concentrations of PCE, TCE, cDCE, and tDCE were expressed as a relative concentration (C/C_o) where the C_o value was the concentration measured with the Summa™ canister and the numerator was the concentration measured with each passive sampler type. The average C/C_o values for each sample were then averaged for each probe size. The results were average C/C_o values of 1.13, 1.10, and 1.19 for the 6-, 12-, and 18-inch probes, respectively. These values are all within 10% of one another, which is within acceptable levels of analytical variability, so the length of the void space does not appear to be a significant factor in the accuracy of the passive sampling data. A similar inspection of the data from 20-, 40-, and 60-min exposures indicated no significant difference (5% level of significance), so for the purpose of plotting all these data together as a single correlation against Summa™ canister results is considered appropriate.

6.1.3.2 Interior Passive Sub-slab Samples

Low uptake versions of the WMS, ATD, and Radiello® samplers were used for the sub-slab sampling at NAS JAX, in an attempt to minimize the starvation effect that was observed with the passive samplers at OTC3. The ATD tube sampler was fitted with a small diameter opening cap, which reduces the uptake rate by about a factor of 10 to about 0.05 mL min^{-1} for TCE, cDCE, and tDCE. The WMS sampler was the smaller (0.8 instead of 1.8 mL) amber vial, which reduces the uptake rate by about a factor of 5 to about 1 mL min^{-1} . The Radiello® sampler was used with the yellow body, which reduces the uptake rate to about 25 to 30 mL min^{-1} .

Sub-slab concentrations for ATD, WMS, and Radiello® passive samplers are presented in Table 14 for TCE, PCE, cDCE, and tDCE. The sub-slab Summa™ canister results are in Table 12. Figure 43 shows the correlation between the passive and Summa™ canister sub-slab measurements. An ideal correlation would have a slope of 1 and an intercept of zero with a correlation coefficient (R^2) of 1.00. The passive samplers all yielded regression lines with a slope very similar to the 1:1 line and R^2 values of 0.71 to 0.95. The Radiello® showed a slight negative bias (regression line coincides with $-2\times$ line), which is not unexpected because it was the sampler with the highest uptake rate, and therefore the greatest risk of starvation. The regression line for the WMS samplers falls within the $\pm 50\%$ range, with a correlation coefficient of 0.95. The regression lines for the ATD sampler showed a slight positive bias (regression line coincides with $2\times$ line) with a correlation coefficient of 0.86. The uptake rates for the ATD sampler with the small diameter cap were calculated based on a ratio of the cross sectional area of the opening of the tube and the standard size cap, not from experimental studies, so the positive bias in the ATD tube data may simply demonstrate uncertainty in the calculated uptake rates.

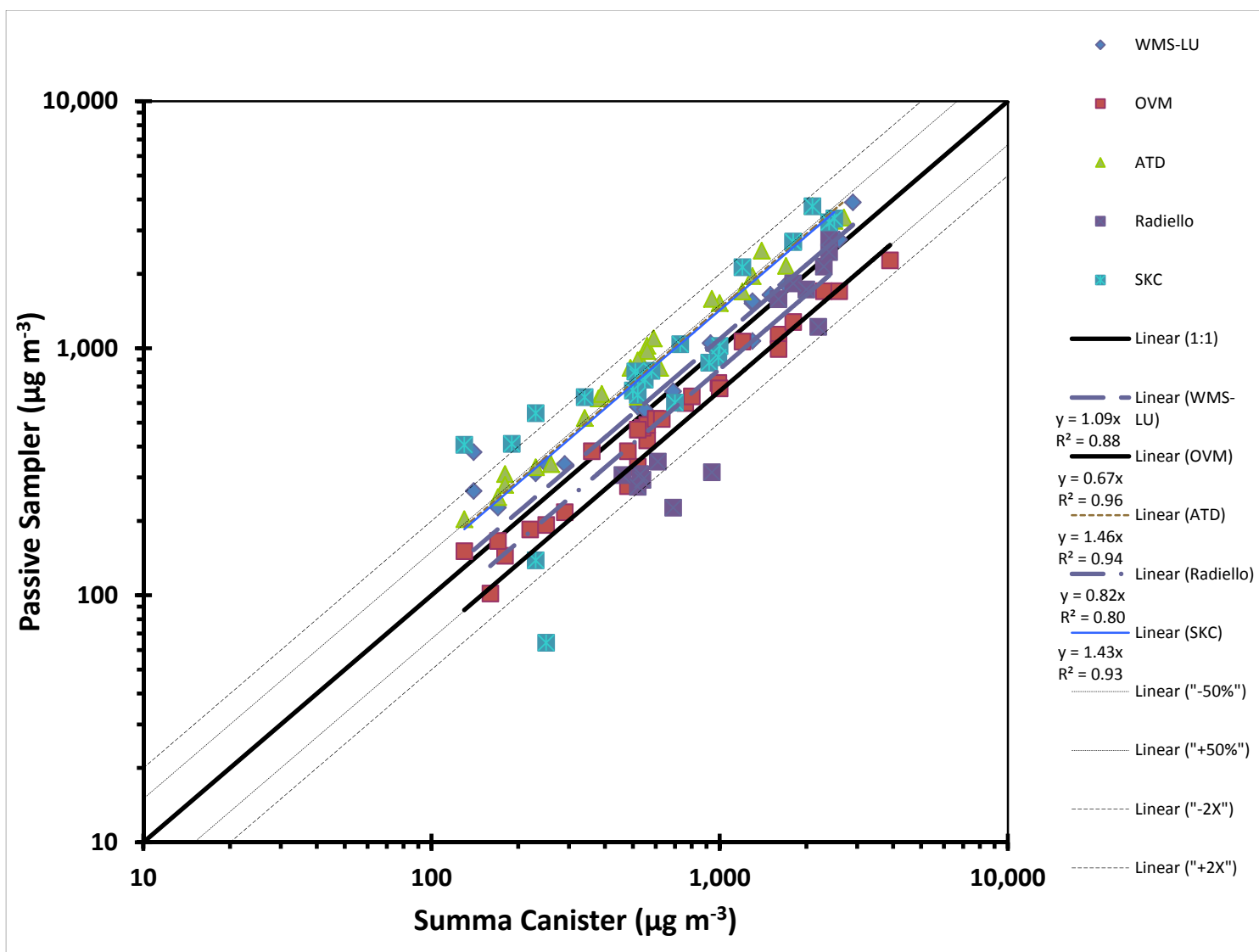


Figure 43. Correlation between soil gas concentrations measured with passive samplers and conventional Summa™ canisters samplers.

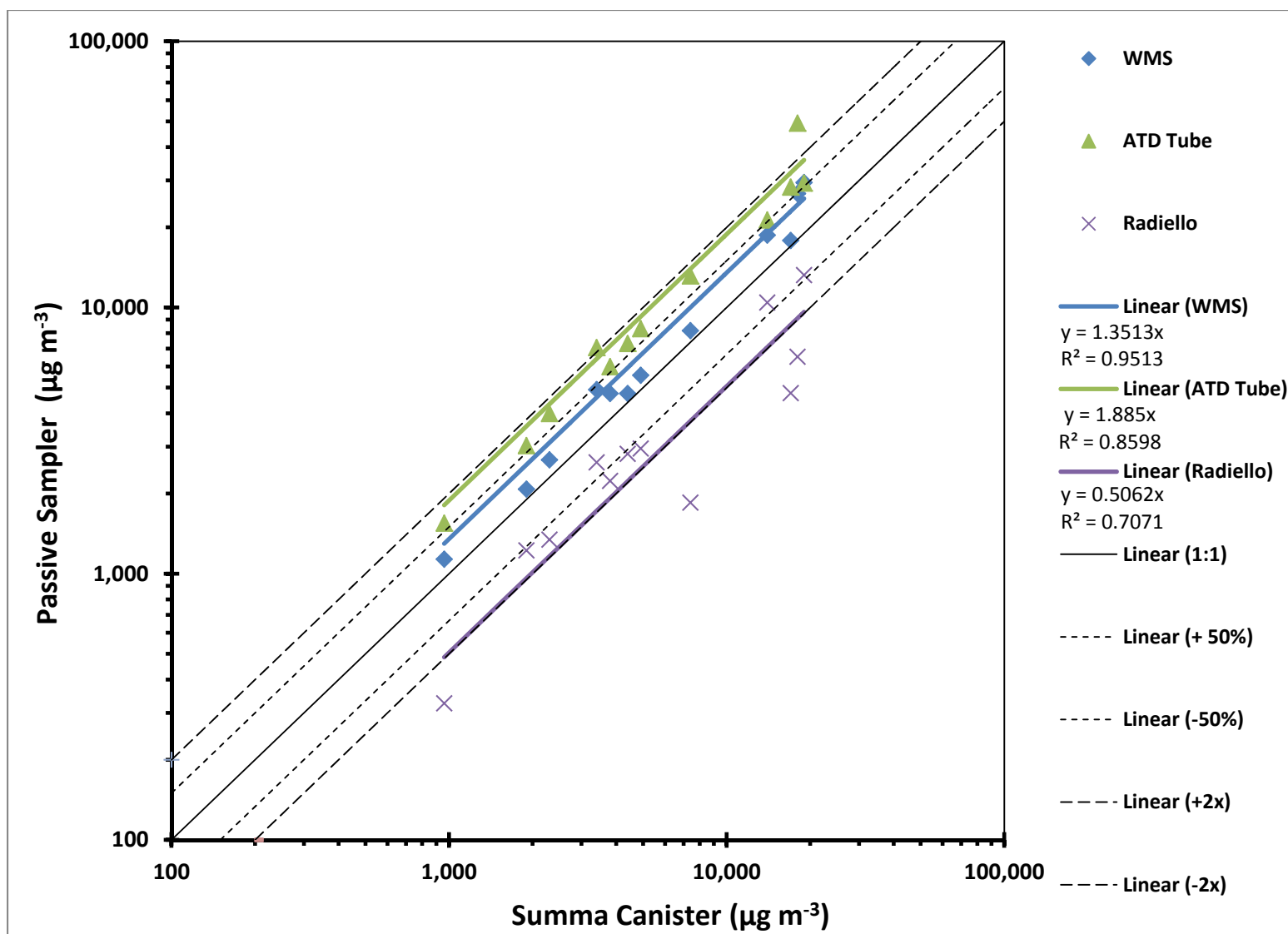


Figure 43. Correlation between passive sub-slab samples and Summa[™] canister samples at NAS JAX.

6.1.3.3 Summary of NAS JAX Results

These data show that the passive samplers provide very consistent and reproducible results, which in many cases are within the $\pm 50\%$ range of the Summa™ canister data. Considering different laboratories and different methods were used to analyze these samples for each of the different samplers, the results for the compounds and locations correlate very well.

Unlike the passive sub-slab vapor sampling from OTC3, there does not appear to be a large negative bias from the starvation effect, which is at least partially attributable to the use of lower uptake rate varieties of the passive samplers. Other explanations are also possible. The NAS JAX sub-slab samples were collected through the floor of a building, whereas at OTC3 samples were collected through a slab located outside the building. This may have had an influence on the pressure differential (building ventilation systems and wind-load can cause a differential pressure between the sub-slab and indoor air), and if so, may have contributed to a modest amount of advection in the sub-slab region. If the building induces pressure gradients that cause even a small amount of flow in the sub-slab soil gas, the magnitude of the starvation effect would be expected to be smaller, particularly for low-uptake-rate samplers.

The passive soil gas data are very encouraging and show a better correlation between passive and active sampler results than any previously published comparisons known to the authors of this report. This may be attributable to the low-uptake rates, probe designs, careful attention to purging after sampler deployment, and sandy soil conditions, and may not apply if all of these conditions and protocols are not incorporated. In the near future, the accuracy of sampling with passive samplers could be improved with some on-going benchmark testing by collecting a certain frequency of duplicate samples (i.e., for every 10 passive samples, add one Summa™ canister sample beside one of the passive samplers). The comparison between the Summa™ canister data and the passive sampler data can be used to derive site-specific and media-specific uptake rates for the compounds that are detectable in both samples. With proper calibration or benchmarking, the consistency of the passive samplers is encouraging. Other benefits such as simple shipping and lower cost (especially for large sampling programs) may provide sufficient incentive to justify the calibration/benchmarking effort.

6.1.4 Overall Summary Results for Each Passive Sampler Type

The results available for each sampler type for all media (indoor air, outdoor air, sub-slab gas, and/or soil gas) from the three demonstration sites were compiled to provide an overall assessment of their respective performance. These plots exclude the results that showed biases that are easily explained (equivalent sample volume far greater than the safe sampling volume or negative bias attributable to starvation where higher uptake samplers were used in low face-velocity settings). The remaining data were compiled into a single graph to illustrate each sampler's correlation to conventional Summa™ canister results over several orders of magnitude of concentration (Figure 44). Each of these plots includes a line from the lower left to the upper right corners representing the ideal correlation.

A linear regression was performed on the data for each sampler to provide statistics on the correlation. The regression would be heavily weighted to the samples with the highest concentrations because of the wide span of data values (roughly seven orders of magnitude total range), so a logarithmic transformation was performed on each (x, y) point (Summa™ canister concentration, passive sampler concentration), and the regression was performed on the transformed data. The intercepts were then reverse transformed (Table 15).

Table 15. Statistics for the correlation between each passive sampler and conventional Summa™ canister VOC measurements for the three demonstration sites.

Sampler	Regression Slope	y Intercept ($\mu\text{g m}^{-3}$)	R²
WMS	1.08	0.6	0.98
3M™ OVM	0.93	1.0	0.98
ATD tube	1.02	1.2	0.98
Radiello®	0.93	1.1	0.97
SKC Ultra	0.97	1.1	0.95

These charts show a strong positive correlation between all five passive sampler types and Summa™ canisters. Some outliers are in the correlation, which may be attributable to individual compounds for which the uptake rate for a particular sampler may be poorly known or calculated, so opportunities exist for improved data quality over time as more studies are conducted and the uptake rates become supported with more data.

6.1.5 Considerations for Sampler Selection

There are many different configurations of passive samplers and, as a result, the selection of the preferred sampler for a particular application depends on the compounds of interest, the desired reporting limit, and the analytical sensitivity (reporting limit). Table 16 shows an example of how this might affect the selection of a sampler. In this case, the residential indoor air screening level corresponding to a 1×10^{-6} incremental lifetime cancer risk is listed as a reference concentration and the exposure duration required for each of the passive samplers to achieve a reporting limit equal to the screening level is also shown. In some cases, the exposure duration may be longer than practical (e.g., chloroform, VC). Some blanks in the table are for combinations of samplers where the uptake rate is not well known or the specific compound is not suited for use with a specific sorbent. In general, the thermal desorption methods of analysis provide better sensitivity, and therefore can meet the data quality objective of reporting limits at or below screening levels with a shorter exposure duration (e.g., benzene).

However, the thermally desorbable sorbents are also weaker sorbents and may experience poor retention for longer exposure duration, or higher uptake rates. Therefore, it is also worthwhile to compare the equivalent sample volume to the recommended safe sampling volume for the thermally desorbable sorbents.

Currently, there is on-going research to improve the understanding of how site-specific conditions (wind-speed, temperature, humidity, concentration, and exposure duration) may influence the uptake rate (ESTCP ER-0830). Preliminary indications are that these factors are significant and that it may be appropriate to customize the uptake rate to some degree to account for changes in sampling conditions. Meanwhile, the accuracy of sampling with passive samplers can be improved with some benchmarking through collection of a certain frequency of duplicate samples (i.e., for every 10 passive samples, add one Summa™ canister sample beside one of the passive samplers). The comparison between the Summa™ canister data and the passive sample data can be used to derive site-specific and media-specific uptake rates for the compounds that are detectable in both samples. With proper calibration/benchmarking, the consistency of the passive samplers is encouraging.

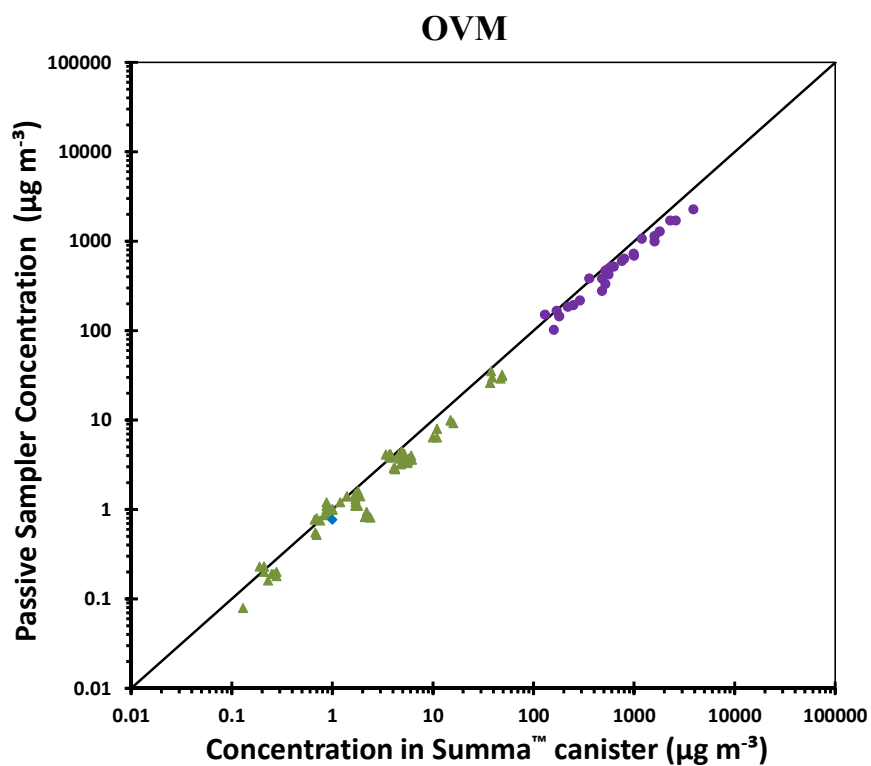
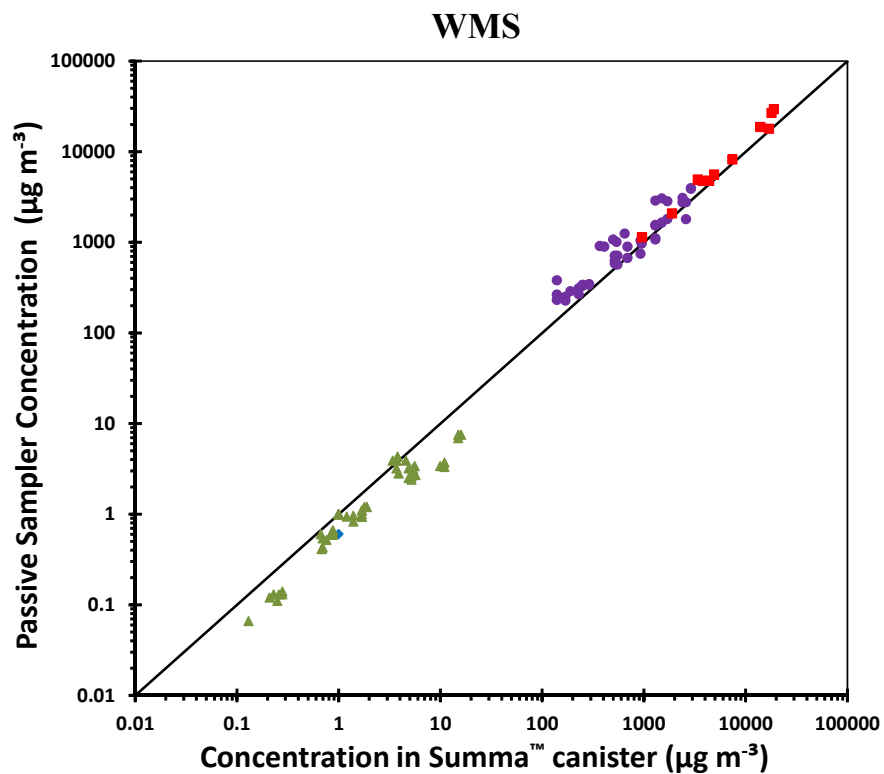


Figure 44. Comparison between all the accepted measurements for the three demonstration sites with each passive sampler vs. conventional Summa™ canister.

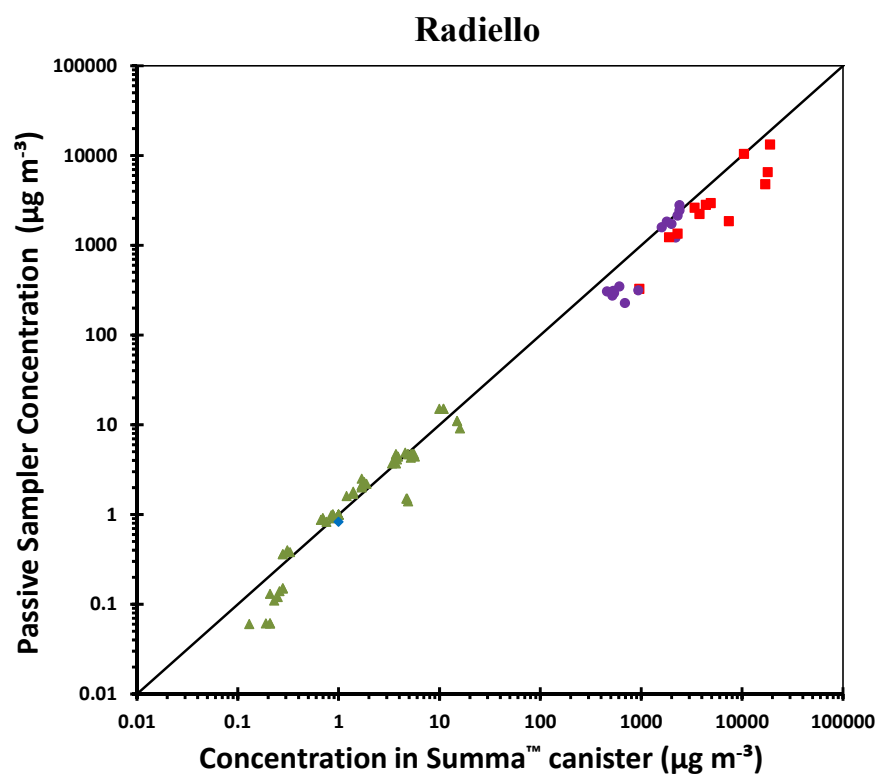
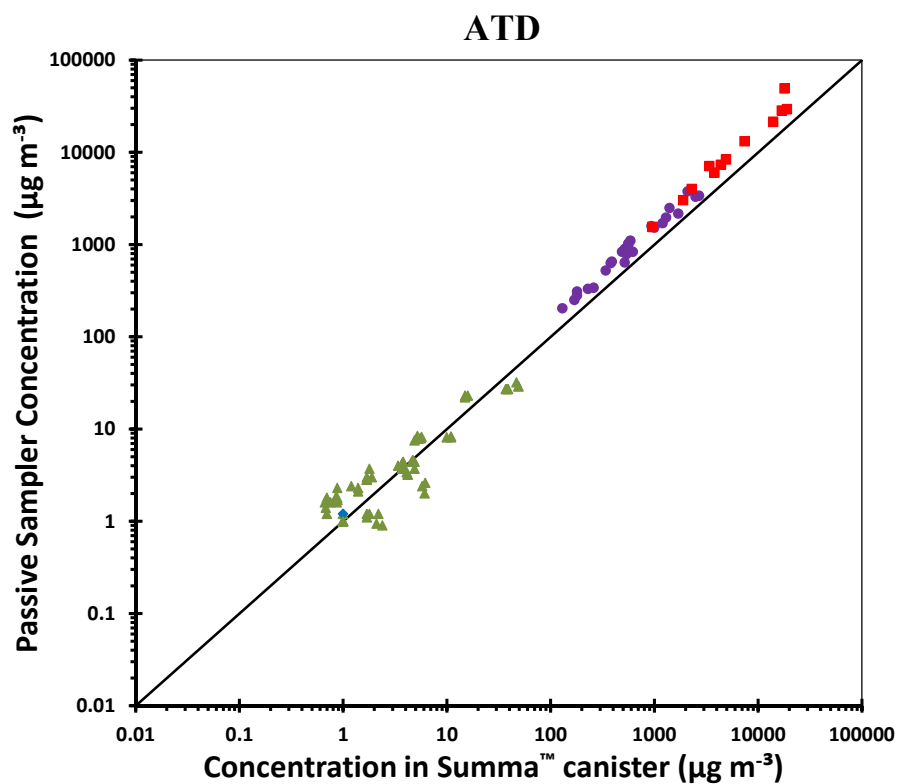


Figure 44. Comparison between all the accepted measurements for the three demonstration sites with each passive sampler vs. conventional Summa™ canister. (continued)

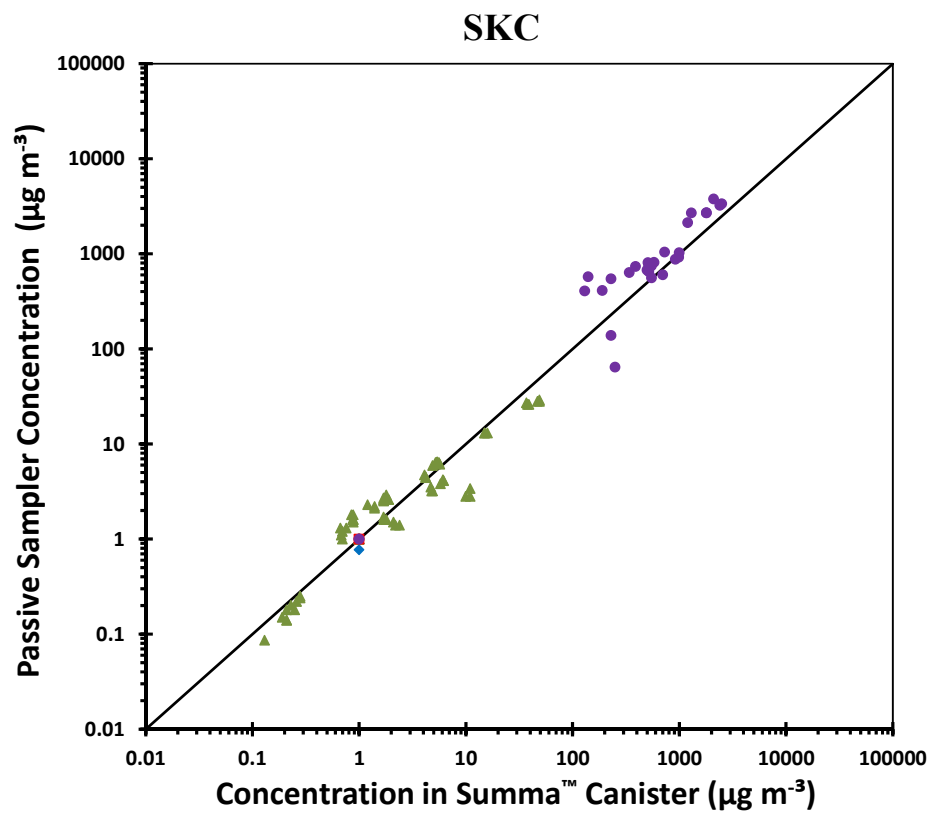


Figure 44. Comparison between all the accepted measurements for the three demonstration sites with each passive sampler vs. conventional Summa™ canister. (continued)

Table 16. Exposure time for selection of appropriate single-unit or set of passive samplers for indoor air screening. The reference concentration is the residential indoor air screening level corresponding to a 1×10^{-6} incremental lifetime cancer risk. The exposure duration required for each passive sampler with either solvent or thermal analysis to achieve a reporting limit equal to the screening level is provided.

Compound	Residential Indoor Air Screening Level ($\mu\text{g m}^{-3}$)	WMS		ATD Tube		Radiello		SKC Ultra		3M™ OVM
		Solvent Extraction	Thermal Desorption	Tenax TA	Carbopack B	Solvent Extraction	Thermal Desorption	Solvent Extraction	Thermal Desorption	Solvent Extraction
		Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)	Exposure Time (hr)
1,1,1-Trichloroethane	5,200	0.13	0.01	0.03	0.03	0.01	0.00	0.03	0.00	0.01
1,1,2,2-Tetrachloroethane	0.042	2802.44	190.57							
1,1,2-Trichloroethane	0.15	1678.42	184.63	1200.00	1200.00			1182.03	27.19	280.58
1,1-Dichloroethane	1.5	466.85	18.67	88.89	88.89					25.10
1,1-Dichloroethene	210	19.36	0.19	0.56	0.56	0.10	0.00	1.78	0.01	0.36
1,2,4-Trimethylbenzene	7.3	9.15	0.46			4.57	0.23			
1,2-Dichlorobenzene	210	0.27	0.03							0.21
1,2-Dichloroethane	0.094	3436.14	137.45	1418.44	1418.44	230.27	4.61	1248.63	24.97	400.54
1,3,5-Trimethylbenzene	--									
1,3-Dichlorobenzene	--									
1,4-Dichlorobenzene	0.22	289.37	34.72	140.73		148.54				204.38
2-Butanone	5,200	0.13	0.15	0.14		0.04		0.02	0.01	0.01
4-Methyl-2-pentanone	3,100	0.17	0.03							
Acetone	32,000	0.08	0.01			0.00		0.01	0.00	0.00
Benzene	0.31	2500.63	400.10	132.34		134.41	33.60	672.04	53.76	227.17
Carbon Tetrachloride	0.41	1355.01	84.01			60.67				100.95
Chlorobenzene	52	3.01	0.14			0.47				0.82
Chloroform	0.11	3885.00	186.48			202.02				339.21
Chloromethane	94	77.09								
cis-1,2-Dichloroethene	--									
Cyclohexane	6,300	0.06	0.00	0.01						0.01
Ethylbenzene	0.97	129.58	5.70	36.94	246.28	252.68	5.05	133.19	2.93	47.20
Heptane	--									
Hexane	730	1.10	0.40					0.16	0.03	0.05
m,p-Xylene	100	1.33	0.06		2.39	0.24	0.12	1.33	0.03	
MTBE	9.4	72.08	2.59			2.73		13.04	2.35	4.32
Naphthalene	0.072	451.41	23.47	45.39		925.93				705.74
o-Xylene	100	1.18	0.05		2.39	0.26	0.13	1.40	0.03	
Propylbenzene	1,000	0.09	0.04			0.03				
Styrene	1,000	0.12	0.01	0.04		0.03	0.01	0.16		0.04
Tetrachloroethene	0.41	379.91	25.83	98.72	674.20	68.90	3.44	329.42	13.18	
Toluene	5,200	0.04	0.00	0.01	0.01	0.00	0.00	0.02	0.00	0.01
trans-1,2-Dichloroethene	63	20.04	0.40	2.35	2.36	0.43	0.01	3.58	0.04	1.43
Trichloroethene	1.2	212.37	11.47	150.00	150.00	20.13	1.01	93.21	2.52	33.49
Vinyl Chloride	0.16	43402.78		404.23						765.93

6.2 BUILDING PRESSURE CONTROL - RESULTS

The demonstration of building pressure control was completed in six buildings. The scope of each demonstration is summarized in Table 17. In four buildings, testing was conducted under controlled negative and positive pressure conditions. For the remaining two buildings, testing was conducted under baseline (i.e., uncontrolled pressure) and controlled negative and positive pressure conditions. The testing in the last two buildings was conducted twice to evaluate the reproducibility of the method.

Table 17. Summary of pressure control testing program at each demonstration site.

Demonstration Building	Pressure Conditions Tested	Number of Testing Events
Building 828, Travis AFB	Controlled negative pressure-controlled positive pressure	One
Building 103, NAS JAX	Controlled negative pressure-controlled positive pressure	One
Parris Island new dry cleaner facility	Controlled negative pressure-controlled positive pressure	One
Building 102, Tinker AFB	Controlled negative pressure-controlled positive pressure	One
ASU Research House, Hill AFB	Baseline (i.e., uncontrolled pressure)-controlled negative pressure-controlled positive pressure	Two
Building 107, Moffett Field	Baseline (i.e., uncontrolled pressure)-controlled negative pressure-controlled positive pressure	Two

6.2.1 Air Exchange Rate

For each demonstration building, the air exchange rate was determined based on the SF₆ release rate and the concentration of SF₆ measured in indoor air. No indoor air tracer was used for the Tinker AFB demonstration due to an error in ordering the tracer gas. As a result, air exchange rates could not be calculated for this building. The results for air exchange rate are summarized in Table 18.

For the demonstrations, air exchange rates were comparable between the negative pressure test condition and the positive pressure test condition. The median change in air exchange between the two controlled pressure conditions was 16%, with a maximum change of 67% for Travis AFB Building 828.

For a building where the air exchange is higher under the positive pressure condition compared to the negative pressure condition, a decrease in VOC concentration during the positive pressure condition could be attributable either to the increased air exchange rate, or to the suppression of vapor intrusion by the positive pressure condition. The air exchange rate was higher under positive pressure conditions for only two of the demonstrations, Travis AFB Building 828 with an increase in air exchange rate of 67% between the negative pressure and positive pressure measurement events, and Moffett Field Building 107 with an 8% increase.

If the change in air exchange rate were the only factor affecting the change in VOC concentration then the expected concentration under positive pressure conditions would be

$$\text{Predicted } C_{pp} = \text{Measured } C_{np} \left(\frac{AER_{np}}{AER_{pp}} \right),$$

where,

Predicted C_{pp} = Predicted chemical concentration under positive pressure conditions

Measured C_{np} = Measured chemical concentration under negative pressure conditions

AER_{np} = Air exchange rate under negative pressure conditions

AER_{pp} = Air exchange rate under positive pressure conditions

Table 18. Building air exchange rates (day⁻¹).

Demonstration Building	Baseline	Negative Pressure	Positive Pressure
Building 828, Travis AFB	NM	49 day ⁻¹	82 day ⁻¹
Building 103, Jacksonville NAS	NM	15 day ⁻¹	14 day ⁻¹
Parris Island New Dry Cleaner Facility	NM	37 day ⁻¹	32 day ⁻¹
Building 102, Tinker AFB	NM	NM	NM
ASU Research House, Hill AFB (Round 1)	2.4 day ⁻¹	19 day ⁻¹	13 day ⁻¹
ASU Research House, Hill AFB (Round 2)	4.3 day ⁻¹	29 day ⁻¹	27 day ⁻¹
Building 107, Moffett Field (Round 1)	10 day ⁻¹	63 day ⁻¹	42 day ⁻¹
Building 107, Moffett Field (Round 2)	8.2 day ⁻¹	48 day ⁻¹	52 day ⁻¹

NM = Not measured.

At the first 4 sites, baseline measurements were not included in the planned activities.

At Tinker AFB, the tracer gas was not available.

The comparison between the measured and predicted concentrations for TCE and radon for Travis AFB Building 828 is shown in Table 19. In this building, the air exchange rate under controlled pressure conditions (either negative or positive) was five to seven times higher than baseline conditions. This analysis indicated that the change in air exchange rates was not the primary cause of the change in chemical concentration in indoor air between the two sample events. Taken as a whole, the evaluation of building air exchange rate under controlled negative and positive conditions indicates that differences in air exchange rate are typically not a significant contributor to changes in VOC concentrations measured in indoor air between the two controlled-pressure conditions.

Table 19. Predicted* versus measured chemical concentrations under positive pressure conditions in Travis AFB Building 828.

Chemical	Measured C_{np}	Predicted C_{pp}	Measured C_{pp}
TCE	0.15 ± 0.081 µg m ⁻³	0.089 µg m ⁻³	<0.036 ± 0.003 µg m ⁻³
Radon	0.67 ± 0.058 pCi L ⁻¹	0.40 pCi L ⁻¹	0.27 ± 0.058 pCi L ⁻¹

*Predicted concentration is change in air exchange rate were the only factor affected is concentration.

Note: This calculation does not apply to VOCs with exclusively ambient sources (i.e., benzene and toluene).

6.2.2 Chemical Concentrations

For each demonstration building, chemical concentrations were measured at three sub-slab sample points, three indoor air, and one ambient air locations. The measured concentrations are summarized in Table 20.

6.2.3 Cross-Foundation Pressure Gradients

For each demonstration building, foundation permeability was evaluated by comparing the cross-foundation pressure gradient to the pressure gradient across the building envelope (Table 19 and Table 21).

6.2.4 Collection of Data Representative of Site Conditions

The collection of site data representative of actual site conditions was achieved by adhering to the sampling and analysis procedures specified in Section 5. QA/QC samples were collected to allow for the evaluation of data precision, accuracy, completeness, representativeness, and comparability.

6.2.4.1 Data Quality Review

The analytical results for sub-slab vapor, indoor, and ambient air were reviewed to evaluate data usability. The data were screened based on (1) sampling procedures, (2) custody procedures, (3) precision assessment, (4) accuracy assessment, and (5) completeness.

Sampling Procedures. Air and soil gas samples submitted for laboratory analysis were collected in accordance with Standard Operating Procedures (SOPs) routinely used by GSI Environmental Inc. (GSI) or sample collection methods described in the ESTCP Project ER-200707 Final Report (<http://www.serdp.org/content/download/15883/181700/file/ER-200707-FR.pdf>). The following deviations from planned procedures occurred during the field program:

- At Tinker AFB, the indoor air tracer gas (SF₆) was not used because the correct gas cylinder could not be obtained in time for the demonstration.
- At Moffett Field, VOCs by U.S. EPA Method TO-15 (U.S. EPA, 1999a) could not be analyzed from the Sub-slab-1 sample from baseline conditions on 29 October 2010, because of a SummaTM canister valve malfunction. TO-15 analysis also could not be conducted on the Sub-slab-2 sample from the positive pressure condition on 31 October 2010 because of debris in the threads of the canister valve.
- The evaluation was conducted twice in a row at Hill AFB (ASU Research House) and at Moffett Field. Sub-slab radon was measured with a RAD7 portable radon detector (DurrIDGE Company, Billerica, Massachusetts) during both rounds of sampling at each site. Sub-slab samples were collected in Tedlar[®] bags for radon laboratory analysis only during the second round of sampling. Indoor and ambient air samples were collected in Tedlar[®] bags for radon analysis during both rounds of sampling at each site.

Custody Procedures, Holding Time. All samples submitted for analysis were received within the required holding times. All samples were submitted under chain-of-custody control with no indication of any losses of custody. Chain of custody documentation was provided by the final recipient of the samples to document the complete series of custody transactions.

Table 20. Chemical concentrations in demonstration buildings.

		Baseline Pressure			Negative Pressure			Positive Pressure		
		Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air
Building 828, Travis AFB										
Benzene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	0.43 ± 0.036	0.60 ± 0.11	0.70	$< 0.41 \pm 0.006$	0.54 ± 0.061	0.50
Toluene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	$< 2.03 \pm 0.058$	1.23 ± 0.37	1.30	$< 2.03 \pm 0.058$	0.77 ± 0.14	0.53
SF ₆ ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	$< 9.75 \pm 0.13$	92 ± 17	< 8.9	10.2 ± 0.72	56 ± 42	< 9.1
TCE ($\mu\text{g m}^{-3}$)	SS	NM	NM	NM	1.17 ± 1.3	0.15 ± 0.081	< 0.038	1.07 ± 1.15	$< 0.036 \pm 0.003$	< 0.037
Radon (pCi L ⁻¹)	SS	NM	NM	NM	978 ± 248	0.67 ± 0.058	0.4	971 ± 140	<u>0.27 ± 0.058</u>	0.3
Building 103, Jacksonville NAS										
Benzene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	$< 23 \pm 12$	0.57 ± 0.021	0.63	$< 22 \pm 11$	<u>0.73 ± 0.015</u>	0.56
Toluene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	$< 115 \pm 57$	3.22 ± 0.55	2.10	$< 109 \pm 56$	4.23 ± 1.4	1.50
SF ₆ ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	12 ± 3.7	158 ± 140	9.2	21 ± 13	170 ± 100	9.4
PCE ($\mu\text{g m}^{-3}$)	SS	NM	NM	NM	$19,700 \pm 9,300$	1.67 ± 0.25	0.15	$19,333 \pm 8,100$	<u>0.74 ± 0.20</u>	0.14
TCE ($\mu\text{g m}^{-3}$)	SS	NM	NM	NM	$3,050 \pm 1,300$	0.38 ± 0.080	0.12	$2,633 \pm 780$	0.23 ± 0.06	0.04
Radon (pCi L ⁻¹)	SS	NM	NM	NM	142 ± 16	0.23 ± 0.15	0.1	134 ± 38	0.1 ± 0	0.1
Parris Island New Dry Cleaner Facility										
Benzene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	2.0 ± 1.2	0.43 ± 0.023	0.46	0.75 ± 0.27	<u>0.69 ± 0.015</u>	0.84
Toluene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	6.0 ± 3.9	10 ± 4.6	1.6	2.3 ± 0.06	5.3 ± 0.25	2.7
SF ₆ ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	7.1 ± 1.0	109 ± 57	< 10	$< 6.4 \pm 0$	119 ± 57	< 9.1
PCE ($\mu\text{g m}^{-3}$)	SS*	NM	NM	NM	153 ± 56	21 ± 8.9	0.29	108 ± 46	<u>47 ± 9.6</u>	0.43
Radon (pCi L ⁻¹)	SS	NM	NM	NM	$2,498 \pm 190$	0.26 ± 0.046	0.11	$2,337 \pm 230$	0.38 ± 0.12	0.22

Table 20. Chemical concentrations in demonstration buildings. (Continued)

		Baseline Pressure			Negative Pressure			Positive Pressure		
		Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air
Building 102, Tinker AFB										
Benzene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	10 \pm 16	0.66 \pm 0.15	0.66	4.2 \pm 4.6	0.40 \pm 0.008	0.56
Toluene ($\mu\text{g m}^{-3}$)	AG	NM	NM	NM	17 \pm 15	5.87 \pm 0.7	8.5	9.2 \pm 3.1	<u>0.59 \pm 0.064</u>	1.7
PCE ($\mu\text{g m}^{-3}$)	SS	NM	NM	NM	43 \pm 33	4.7 \pm 2.8	5.9	<u>26 \pm 32</u>	0.34 \pm 0.063	1.2
Radon (pCi L ⁻¹)	SS	NM	NM	NM	86 \pm 82	0.25 \pm 0.072	0.21	37 \pm 57	0.18 \pm 0.026	0.27
ASU Research House, Hill AFB (Round 1)										
Benzene ($\mu\text{g m}^{-3}$)	AG	0.25 \pm 0.12	0.48 \pm 0.07	0.50	0.94 \pm 0.63	0.45 \pm 0.01	0.39	0.21 \pm 0.12	0.55 \pm 0.07	0.54
Toluene ($\mu\text{g m}^{-3}$)	AG	3.15 \pm 3.97	2.20 \pm 0.40	1.50	2.04 \pm 1.72	<u>1.40 \pm 0.17</u>	0.87	0.81 \pm 0.46	<u>2.47 \pm 0.40</u>	2.20
SF ₆ ($\mu\text{g m}^{-3}$)	AG	2,333 \pm 1,656	8,900 \pm 1,825	12	56.3 \pm 64.0	<u>1,113 \pm 1,115</u>	< 9.8	1,227 \pm 748	1,595 \pm 1,419	<12
DCE ($\mu\text{g m}^{-3}$)	SS	5.40 \pm 9.18	0.13 \pm 0.02	< 0.04	169 \pm 132	6.10 \pm 5.24	< 0.04	6.52 \pm 9.95	0.04 \pm 0.003	<0.05
TCE ($\mu\text{g m}^{-3}$)	SS	11.4 \pm 8.86	6.80 \pm 0.44	0.21	220 \pm 182	9.80 \pm 7.30	0.12	6.90 \pm 4.42	0.33 \pm 0.22	0.13
Radon (pCi L ⁻¹)	SS	252 \pm 364	0.39 \pm 0.06	0.48	261 \pm 313	2.44 \pm 1.49	0.18	211 \pm 337	0.03 \pm 0.06	0.09
ASU Research House, Hill AFB (Round 2)										
Benzene ($\mu\text{g m}^{-3}$)	AG	0.39 \pm 0.03	0.46 \pm 0.02	0.39	<u>0.74 \pm 0.10</u>	0.46 \pm 0.02	0.42	0.45 \pm 0.11	<u>0.57 \pm 0.02</u>	0.57
Toluene ($\mu\text{g m}^{-3}$)	AG	2.70 \pm 0.98	4.08 \pm 2.41	3.90	5.42 \pm 5.70	3.07 \pm 1.19	1.90	2.53 \pm 1.01	2.27 \pm 0.45	1.8
SF ₆ ($\mu\text{g m}^{-3}$)	AG	750 \pm 823	5200 \pm 1253	< 8.8	53.3 \pm 57.9	<u>780 \pm 710</u>	12	990 \pm 615	867 \pm 810	11
DCE ($\mu\text{g m}^{-3}$)	SS	4.78 \pm 7.13	0.12 \pm 0.01	< 0.04	231 \pm 188	6.23 \pm 4.41	< 0.04	7.54 \pm 10.8	<0.04 \pm 0.004	<0.04
TCE ($\mu\text{g m}^{-3}$)	SS	10.3 \pm 3.52	18.8 \pm 3.33	0.17	268 \pm 225	9.47 \pm 6.07	0.15	9.60 \pm 3.03	0.15 \pm 0.04	0.06
Radon (pCi L ⁻¹)	SS	184 \pm 234	0.38 \pm 0.14	0.10	207 \pm 179	1.87 \pm 1.99	0.03	168 \pm 262	0.09 \pm 0.07	0.07

Table 20. Chemical concentrations in demonstration buildings. (Continued)

		Baseline Pressure			Negative Pressure			Positive Pressure		
		Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air	Sub-slab	Indoor Air	Ambient Air
Building 107, Moffett Field (Round 1)										
Benzene ($\mu\text{g m}^{-3}$)	AG	12.5 \pm 16.3	0.45 \pm 0.01	0.46	4.22 \pm 3.85	<u>0.26 \pm 0.02</u>	0.27	2.51 \pm 2.67	0.49 \pm 0.19	0.40
Toluene ($\mu\text{g m}^{-3}$)	AG	23.0 \pm 24.0	1.83 \pm 0.31	2.10	13.8 \pm 9.89	<u>1.29 \pm 0.42</u>	3.40	8.15 \pm 6.86	5.13 \pm 5.16	1.60
SF ₆ ($\mu\text{g m}^{-3}$)	AG	39.7 \pm 48.0	1,600 \pm 200	<9.1	53.0 \pm 38.9	<u>257 \pm 120</u>	<9.1	234 \pm 183	387 \pm 49	<11
PCE ($\mu\text{g m}^{-3}$)	SS	3.15 \pm 0.49	1.90 \pm 0.26	0.08	2.48 \pm 1.55	1.57 \pm 0.31	0.05	2.15 \pm 1.34	<u>0.10 \pm 0.03</u>	0.06
TCE ($\mu\text{g m}^{-3}$)	SS	1.35 \pm 1.35	2.93 \pm 0.32	0.05	2.15 \pm 1.58	<u>2.33 \pm 0.42</u>	<0.04	1.55 \pm 0.92	<u>0.09 \pm 0.04</u>	0.05
Radon (pCi L ⁻¹)	SS	406 \pm 210	0.65 \pm 0.09	0.12	333 \pm 259	0.46 \pm 0.20	0.03	250 \pm 312	<u>0.06 \pm 0.11</u>	0.05
Building 107, Moffett Field (Round 2)										
Benzene ($\mu\text{g m}^{-3}$)	AG	1.37 \pm 1.19	1.12 \pm 0.03	1.10	1.06 \pm 0.83	<u>1.57 \pm 0.12</u>	1.50	1.03 \pm 0.41	1.53 \pm 0.06	1.4
Toluene ($\mu\text{g m}^{-3}$)	AG	4.20 \pm 2.69	4.00 \pm 0.30	3.50	3.72 \pm 1.91	9.57 \pm 4.92	9.40	4.10 \pm 0.66	8.50 \pm 0.10	10.0
SF ₆ ($\mu\text{g m}^{-3}$)	AG	1,200 \pm 954	3,300 \pm 265	18	118 \pm 70.9	<u>563 \pm 237</u>	16	470 \pm 341	530 \pm 450	18
PCE ($\mu\text{g m}^{-3}$)	SS	2.02 \pm 1.18	2.83 \pm 0.12	0.12	3.16 \pm 2.64	2.00 \pm 0.56	0.21	1.63 \pm 1.37	<u>0.42 \pm 0.02</u>	0.89
TCE ($\mu\text{g m}^{-3}$)	SS	2.01 \pm 1.10	4.95 \pm 0.22	0.08	1.85 \pm 0.68	<u>3.13 \pm 0.91</u>	0.12	1.15 \pm 1.01	<u>0.12 \pm 0.02</u>	0.09
Radon (pCi L ⁻¹)	SS	297 \pm 279	1.00 \pm 0.05	0.18	374 \pm 226	0.62 \pm 0.16	0.26	357 \pm 342	0.30 \pm 0.10	0.33

Table 21. Average cross-building envelope and cross-foundation pressure gradients during demonstrations.

Site	Average Pressure Gradient (Pa)	
	Cross-Building Envelope	Cross-Foundation
Travis AFB	NP: -2.9 PP: +2.4	NP: -0.15 (5%) PP: +0.002 (<1%)
Jacksonville NAS	NP: -0.15 PP: +1.9	NP: +0.05 (-33%) PP: -0.005 (<-1%)
Parris Island	NP: -3.9 PP: -2.0	NP: +0.10 (-3%) PP: +0.53 (-27%)
Tinker AFB	NP: -15.2 PP: +11.1	NP: -4.5 (30%) PP: +2.0 (18%)
Hill AFB (Round 1)	BL: NM NP: NM PP: NM	BL: +0.91 NP: -2.0 PP: +2.8
Hill AFB (Round 2)	BL: +0.87 NP: -5.2 PP: +3.9	BL: +0.35 (40%) NP: -2.1 (41%) PP: +2.6 (66%)
Moffett Field (Round 1)	BL: -0.49 NP: -2.3 PP: +1.1	BL: -0.19 (39%) NP: -1.5 (66%) PP: +0.45 (39%)
Moffett Field (Round 2)	BL: -0.84 NP: -2.5 PP: +1.0	BL: -0.24 (29%) NP: -1.2 (50%) PP: +0.46 (45%)

Note: Average pressure gradient is average of readings automatically recorded every 5 to 15 minutes during period of induced pressure control. Negative value indicates that pressure inside building is lower than outside building. BL = baseline pressure test condition, NP = negative pressure test condition, PP = positive pressure test condition.

Sub-slab vapor and ambient and indoor air samples from Travis AFB, Tinker AFB, NAS JAX, Parris Island Marine Base, Hill AFB, and Moffett Field NAS were analyzed by Columbia Analytical Services, Simi Valley, California. Radon samples collected for laboratory analysis were all analyzed by the University of Southern California, Los Angeles, California. Sample handling was conducted according to the laboratories' quality assurance programs and the chain of custody.

Precision Assessment: Duplicate Samples, Laboratory Control Sample (LCS), and Laboratory Control Sample Duplicate (LCSD). The precision assessment evaluates the agreement in analytical results between duplicate samples (field duplicates and laboratory duplicates). Precision was evaluated by calculating the RPD between duplicate samples.

Field Precision. Twenty field duplicate samples were collected from the demonstration sites: 11 duplicate soil gas or sub-slab samples, 7 duplicate indoor air samples, and 2 duplicate ambient air samples. The precision objective for the field samples was an RPD $\leq 30\%$. Relative percent difference values for duplicate samples were calculated for seven key VOCs (1,1-DCE, benzene, cDCE, PCE, TCE, toluene, and VC) plus the tracers SF₆ and radon. RPDs were only calculated when these compounds were detected in at least one sample in each normal-duplicate pair analyzed. In the case that either the sample or the duplicate result was reported as non-detect and the second sample resulted in a reported detection, the RPD was calculated based on the difference between the reported detection limit for the non-detect sample and the detected result for the other sample. For example, the sub-slab vapor concentration for SF₆ at the Parris Island Recruit Depot was reported as ND ($<6.6 \mu\text{g m}^{-3}$), with the duplicate reported as a detection of $10.0 \mu\text{g m}^{-3}$. The RPD value for this COC was calculated based on sub-slab SF₆ concentrations of $6.6 \mu\text{g m}^{-3}$ and $10.0 \mu\text{g m}^{-3}$. Results of the field duplicate analysis are summarized in Table 22.

Table 22. Summary of field duplicate precision.

Matrix	Total RPD Calculations	Relative Percent Difference		
		$\leq 30\%$	30–67%	$> 67\%$
Sub-slab and soil gas	44	36	6	2
Indoor air	47	39	7	1
Ambient air	10	2	8	0

Overall, 101 RPD values were calculated for the 9 compounds listed above, with 76% (77 of 101) meeting the RPD criteria of $\leq 30\%$. 21% (21 of 101) of the results that exceeded the RPD criteria had an RPD of less than 67% (twofold difference). Three samples had an RPD greater than 67%.

Laboratory Precision: Laboratory precision of the TO-15 and TO-15 SIM methods is demonstrated by RPD values of laboratory analyzed duplicate samples, which are not field-collected. The RPD results reported by the laboratories for the identified key COCs all meet the criteria of RPD $\leq 25\%$ for the gas analysis methods.

Accuracy Assessment. The objectives for laboratory accuracy were met through analysis of various spike samples (e.g., spikes, matrix spikes, control standards, interference check samples, standard reference samples, and surrogates). The results of the data evaluation based on these objectives are provided below.

Laboratory Accuracy: Laboratory accuracy was assessed based on percent recoveries from matrix spike/matrix spike duplicate (MS/MSD), LCS/LCSD, and surrogate samples. For the key analytes, all samples analyzed by methods TO-15 and TO-15 SIM were acceptable based on the results provided by the laboratories. Although percent recovery control criteria deviations were noted from a few chemicals, none of the chemicals were key compounds and, therefore, the exceedances did not affect interpretation of the results. No VOCs were detected in method blanks.

Completeness Assessment. With the exceptions noted in the section on Sampling Procedures above, all necessary analytical samples were collected and analyzed.

6.2.5 Evaluation of Data Quality Performance Objective

The data quality exceptions noted in the data quality review are typical of environmental field programs and none of these exceptions limit the usability of the results obtained. The results of the data quality review are summarized in Table 23, which shows that the data quality for the

demonstration program data set is acceptable and suitable for evaluation of the demonstration performance.

Table 23. Summary of data evaluation results.

Data Quality Objective (DQO)	Results of Data Quality Evaluation		
	TO-15 SIM	TO-15	Radon
Sampling procedures	Acceptable	Acceptable*	Acceptable
Custody procedures	Acceptable	Acceptable	Acceptable
Holding time	Acceptable	Acceptable	Acceptable
Field duplicate samples	Acceptable*	Acceptable*	Acceptable
LCS/LCSD samples	Acceptable*	Acceptable	N/A
Blank analysis	Acceptable	Acceptable	N/A
Completeness assessment	Acceptable	Acceptable	Acceptable
Overall data usability	Acceptable	Acceptable	Acceptable

Acceptable = This DQO was evaluated and found to have met the requirements outlined in the QAPP. Acceptable* = This DQO was found to have deficiencies or exceptions as discussed in the text however, the data was determined to be usable.

NA = DQO is not applicable to the indicated method.

6.3 VALIDATION OF PRESSURE CONTROL INVESTIGATION PROCEDURE

Full validation of the streamlined evaluation procedure requires two key elements: (1) observation of differences in VOC distribution between negative pressure and positive pressure conditions that support differentiation between vapor intrusion and background sources of VOCs, and (2) a correlation between cross-foundation pressure gradient measurements and the magnitude of observed vapor intrusion.

For each demonstration building, each of the VOCs commonly detected in indoor and sub-slab samples was classified as originating primarily from subsurface sources or indoor sources based on (1) prior knowledge of VOCs present in subsurface sources, and (2) the sub-slab to indoor attenuation factors measured under negative pressure conditions. Under negative pressure conditions, VOCs originating from subsurface sources are expected to have an attenuation factor of <0.1 while VOCs originating from background or indoor sources are expected to have an attenuation factor of >1 . The observed attenuation factors for radon (a subsurface tracer) and SF_6 (an indoor tracer) were used to verify the expected patterns. For all of the demonstration sites, benzene and toluene were identified as originating from above ground sources and detected chlorinated VOCs (PCE, TCE, and/or 1,1-DCE) were identified as originating from subsurface sources.

Based on this preliminary classification, the difference in measured concentrations between negative pressure conditions and positive pressure conditions was evaluated. The predicted concentration changes are illustrated in Figure 45.

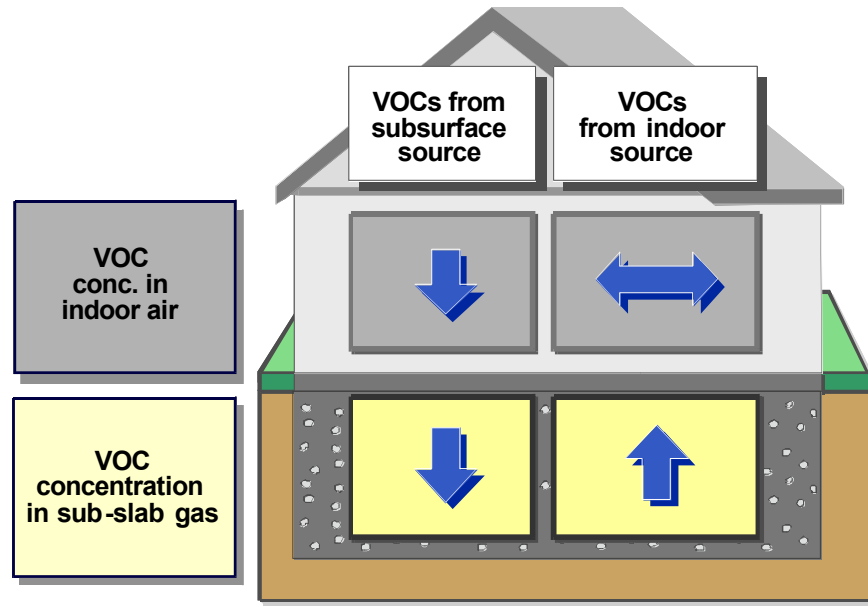


Figure 45. Predicted change in VOC concentration between negative building pressure and positive building pressure sampling events under permeable foundation conditions (e.g., the indoor air concentration of VOCs originating from a subsurface source are expected to be lower under positive building pressure conditions compared to negative building pressure conditions).

6.3.1 Analysis of Variance

For the preliminary data analysis, a factorial analysis of variance (ANOVA) was conducted on the difference in VOC concentration between negative pressure conditions and positive pressure conditions at each measurement location. To control for differences in the magnitude of concentration between COCs, the difference was expressed as the relative percent difference (RPD) in concentration between the negative pressure sampling event and the positive pressure sampling event:

$$RPD = \frac{(C_{NP} - C_{PP})}{\text{Average } (C_{NP}, C_{PP})} \times 100,$$

where,

C_{NP} = COC concentration measured during the negative pressure sampling event

C_{PP} = COC concentration measured during the positive pressure sampling event

Note that the RPD is not represented as an absolute value so that the direction of concentration change (i.e., increase or decrease) between the two pressure conditions is retained. The analytical detection limit was used for non-detect results. For each COC in each demonstration building, this yielded three indoor air measurements and three sub-slab gas measurements. All ANOVA analyses were conducted using the generalized linear model in the MiniTab 13 statistical software package (<http://en.softonic.com/s/minitab-13>).

Initial ANOVA Analysis: The initial ANOVA analysis examined the influence of four factors on the observed difference in COC concentration between the negative and positive pressure sampling events.

In addition, the interaction between these factors was evaluated:

- Sample Matrix: Indoor air samples vs. sub-slab gas samples (1 degree of freedom)
- COC Source: Above ground vs. subsurface (1 degree of freedom)
- Sample Location: The three sample locations established in each demonstration building (2 degrees of freedom)
- Demonstration Site: Travis AFB, Jacksonville NAS, Tinker AFB, Hill AFB, and Moffett Field (4 degrees of freedom)

The results from Parris Island were not included in the analysis because the pressure control was not successful at this location. Based on our prediction (Figure 45), we expected sample matrix, COC source, and the interaction between sample matrix and COC source to be identified as significant factors. Sample location was not predicted to have an effect on the observed difference on COC concentration; however, this factor was included in the initial analysis to evaluate the ability of the model to discriminate between factors predicted to have an effect and factors not predicted to have an effect. The demonstration site was identified as a random factor because the differences between sites were not expected to be predictable.

For this initial analysis, sample matrix ($p = 0.005$) and COC source ($p = 0.030$) were identified significant factors. As expected, the sample location ($p = 0.446$) was not identified as significant. In addition, none of the interactions between factors were identified as significant except for the combined factors of matrix \times location \times source \times site ($p = 0.044$).

Final ANOVA Analysis: Based on the results of the initial ANOVA analysis, sample location was eliminated as a model factor to simplify the model and improve the ability to analyze factor interactions. When sample location was eliminated as a factor, sample matrix, and COC source retained the same level of significance but matrix \times source \times site interaction was also identified as a significant factor ($p = 0.040$).

The results of the ANOVA indicate that the sample matrix, COC source, and matrix \times source \times site interaction have a significant effect on the observed difference in COC concentration between the negative pressure and positive pressure sampling events. In other words, the change in COC concentration between the negative and positive pressure condition is different for COCs originating from different sources (above ground vs. subsurface) and is different for the different measurement matrix (indoor air vs. sub-slab). This is consistent with the predicted effect of building pressure control illustrated in Figure 45.

Based on the site-by-site analysis, the change in COC concentration in indoor air appeared to be more consistent with the predicted change than the change in COC concentration in sub-slab samples. This observation was supported by additional ANOVA analyses. For ANOVA using only the results for indoor air samples, the source (i.e., above ground vs. subsurface) was identified as the only statistically significant factor ($p = 0.03$). For ANOVA using only the results for sub-slab air samples, no model parameters were identified as statistically significant. In other words, the source of the chemical impacts how the concentration changes in indoor air between induced negative and positive pressure conditions; however, this is not a significant factor in how the sub-slab concentration changes.

6.3.2 Site-by-Site Analysis of Results

Although ANOVA is a powerful method to evaluate the statistical significance of specific factors on a large dataset, the method does not evaluate specific trends observed in the data (i.e., did the concentration of COCs originating in the subsurface decrease in indoor air during positive pressure

test conditions?). To further explore whether the observed COC concentration differences matched the prediction provided in Figure 45, t-tests were used to evaluate concentration differences at the individual demonstration sites. Table 20 summarizes the COC concentration measurement results for each demonstration and identifies the cases where the COC concentration under positive pressure conditions was significantly different from negative pressure conditions (t-test, $p < 0.05$). Although the Parris Island demonstration was not considered successful, the results are included for completeness. The observed concentration changes are summarized in Table 24.

Because the demonstration at the Parris Island New Dry Cleaner Facility was not successful, the discussion of the results focuses on the remaining five demonstration buildings.

The comparison between predicted and observed change in concentration between the induced negative and positive pressure testing conditions was based on two factors: (1) whether the concentration trend matched the prediction, and (2) whether the change was statistically significant. For chemicals with an above-ground source (i.e., benzene, toluene, and SF_6), the change in concentration in indoor air between negative and positive pressure conditions matched the prediction (i.e., no change) for 12 out of 20 cases. For four of the remaining eight cases, the increase or decrease in indoor air concentration was matched by a similar change in ambient air concentration, indicating that the change was independent of the change in building pressure condition. For chemicals with a subsurface source (i.e., the chlorinated VOCs), the observed concentration trend in indoor air matched the prediction (i.e., decrease) in 17 of 19 cases; however, the change was statistically significant in only seven cases.

For chemicals with an above-ground source, the change in concentration in the sub-slab matched the prediction (i.e., increase in concentration) in only 5 out of 20 cases. For chemicals with a subsurface source, the concentration change in the sub-slab matched the prediction (i.e., decrease) in only 6 of 19 cases.

The clearest evidence of the utility of building pressure control for evaluation of vapor intrusion is provided by the measurement of radon concentrations in indoor air. At four of the five buildings with successful pressure control, radon concentrations in indoor air were above atmospheric concentrations during negative building pressure and decreased to atmospheric concentrations during positive building pressure. In the fifth building (at Tinker AFB), the radon concentration was similar to atmospheric concentrations during both sampling events indicating an absence of vapor intrusion under all conditions (see Figure 46). For all five of these buildings, the indoor concentration of other COCs with subsurface sources (i.e., the chlorinated VOCs), was either (1) very low (i.e., $<1 \mu\text{g m}^{-3}$) under both the negative pressure condition and the positive pressure condition; or (2) the concentration was much lower under the positive pressure condition compared to the negative pressure condition, matching the pattern observed for radon.

ANOVA analysis indicates that positive vs. negative building pressure does have a statistically significant effect on the distribution of COCs in indoor air and below the building foundation and that the response is dependent on the source of the COC (i.e., subsurface source vs. above-ground source). Two focused ANOVAs using only indoor air data and only sub-slab data indicate that the statistically-significant effect is due to the distribution of COCs in indoor air rather than below the building foundation. This finding is supported by evaluation of the individual site data that indicate that the predicted changes in COC concentration illustrated in Figure 45 generally occur in indoor air but do not typically occur below the building foundation.

Table 24. Observed change in concentration between building test conditions.

Chemical	Source Type	Concentration Change (Baseline to Negative)		Concentration Change (Negative to Positive)	
		Sub-slab	Indoor	Sub-slab	Indoor
Building 828, Travis AFB					
Benzene	Above ground	NM	NM	No Change	No Change
Toluene	Above ground	NM	NM	No Change	Decrease*
SF ₆	Above ground	NM	NM	No Change	Decrease
TCE	Subsurface	NM	NM	No Change	Decrease
Radon	Subsurface	NM	NM	No Change	<u>Decrease</u>
Building 103, Jacksonville NAS					
Benzene	Above ground	NM	NM	No Change	<u>Increase</u>
Toluene	Above ground	NM	NM	No Change	No Change
SF ₆	Above ground	NM	NM	Increase	No Change
PCE	Subsurface	NM	NM	No Change	<u>Decrease</u>
TCE	Subsurface	NM	NM	No Change	No Change
Radon	Subsurface	NM	NM	No Change	Decrease
Parris Island New Dry Cleaner (Note, demonstration not considered successful)					
Benzene	Above ground	NM	NM	Decrease	<u>Increase*</u>
Toluene	Above ground	NM	NM	Decrease	No Change
SF ₆	Above ground	NM	NM	No Change	No Change
PCE	Subsurface*	NM	NM	No Change	<u>Increase</u>
Radon	Subsurface	NM	NM	No Change	Increase
Building 102, Tinker AFB					
Benzene	Above ground	NM	NM	Decrease	No Change
Toluene	Above ground	NM	NM	Decrease	<u>Decrease*</u>
PCE	Subsurface	NM	NM	<u>Decrease</u>	Decrease*
Radon	Subsurface	NM	NM	Decrease	No Change
ASU Research House, Hill AFB (Round 1)					
Benzene	Above ground	Increase	No Change	Decrease	No Change
Toluene	Above ground	No Change	<u>No Change</u>	Decrease	<u>Increase*</u>
SF ₆	Above ground	Decrease	<u>Decrease</u>	Increase	No Change
DCE	Subsurface	Increase	Increase	Decrease	Decrease
TCE	Subsurface	Increase	No Change	Decrease	Decrease
Radon	Subsurface	No Change	Increase	No Change	Decrease

Table 24. Observed change in concentration between building test conditions. (Continued)

Chemical	Source Type	Concentration Change (Baseline to Negative)		Concentration Change (Negative to Positive)	
		Sub-slab	Indoor	Sub-slab	Indoor
ASU Research House, Hill AFB (Round 2)					
Benzene	Above ground	<i>Increase</i>	No Change	No Change	No Change
Toluene	Above ground	Increase	No Change	Decrease	No Change
SF ₆	Above ground	Decrease	<i>Decrease</i>	Increase	No Change
DCE	Subsurface	Increase	Increase	Decrease	Decrease
TCE	Subsurface	Increase	No Change	Decrease	Decrease
Radon	Subsurface	No Change	Increase	No Change	Decrease
Building 107, Moffett Field (Round 1)					
Benzene	Above ground	Decrease	<i>No Change</i>	No Change	Increase*
Toluene	Above ground	No Change	<i>No Change</i>	No Change	Increase
SF ₆	Above ground	No Change	<i>Decrease</i>	Increase	Increase
PCE	Subsurface	No Change	No Change	No Change	<i>Decrease</i>
TCE	Subsurface	Increase	<i>No Change</i>	No Change	<i>Decrease</i>
Radon	Subsurface	No Change	No Change	No Change	<i>Decrease</i>
Building 107, Moffett Field (Round 2)					
Benzene	Above ground	No Change	<i>No Change</i>	No Change	No Change
Toluene	Above ground	No Change	Increase	No Change	No Change
SF ₆	Above ground	Decrease	<i>Decrease</i>	Increase	No Change
PCE	Subsurface	Increase	No Change	No Change	<i>Decrease</i>
TCE	Subsurface	No Change	<i>No Change</i>	No Change	<i>Decrease</i>
Radon	Subsurface	No Change	No Change	No Change	Decrease

Increase = Average concentration during positive pressure condition more than 150% of the average concentration during negative pressure condition. Decrease = Average concentration during positive pressure condition less than 50% of the average concentration during negative pressure condition. No Change = Average concentration during positive pressure condition between 50% and 150% of the average concentration during negative pressure condition. * = Similar change in concentration observed in ambient air samples. **Decrease** = statistically significant change based on paired t-test.

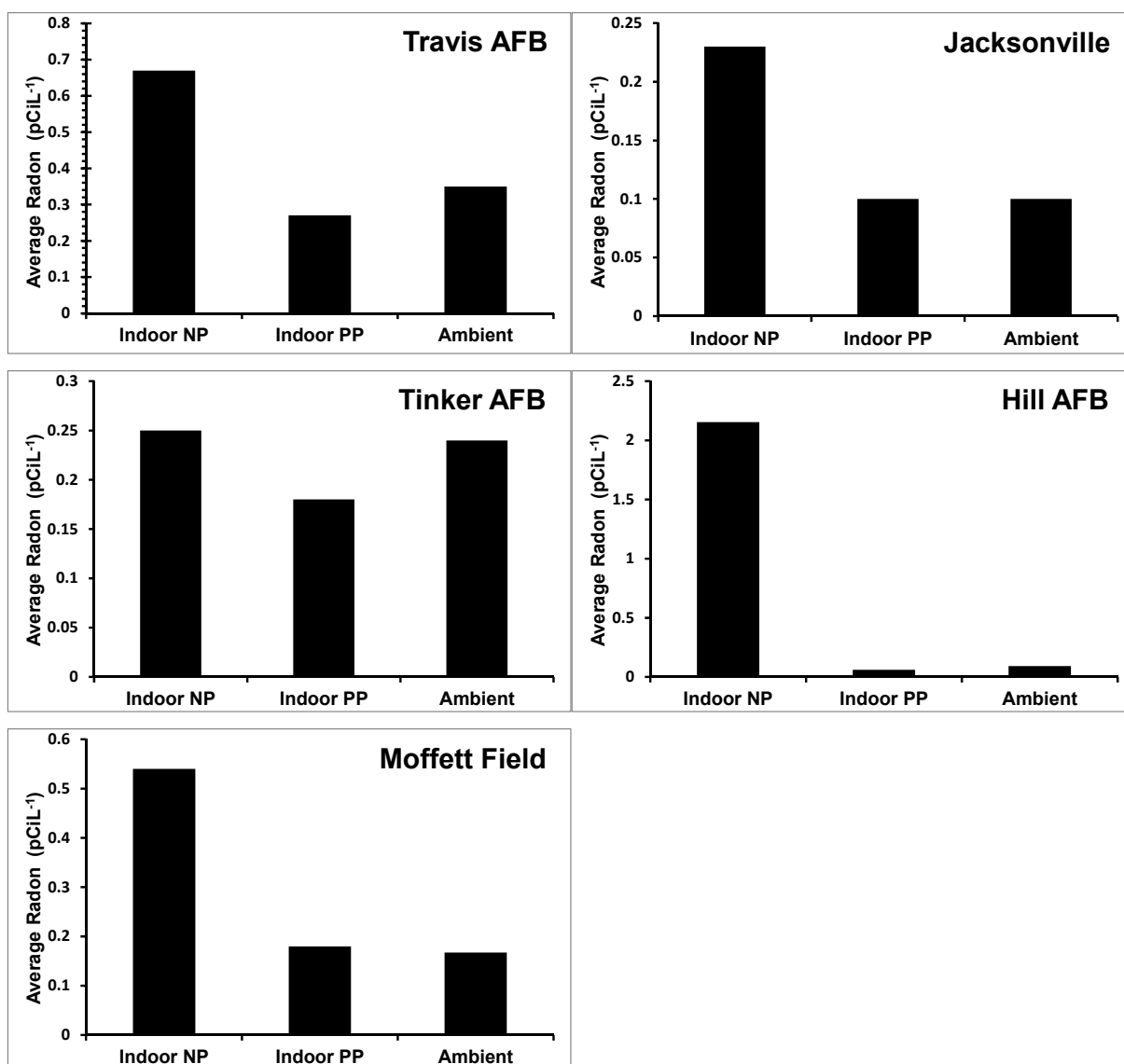


Figure 46. Effect of building pressure control on concentration of radon in indoor air.

6.3.3 Other Analysis of Demonstration Results

The demonstration dataset supports the following additional evaluations and observations.

6.3.3.1 Evaluation of Reproducibility

To evaluate the reproducibility of the investigation procedure, the demonstration was conducted twice in each of the two final demonstration buildings: ASU Research House in Hill AFB and Building 107 in Moffett Field. As shown in Table 20 and Figure 47, the change in COC concentrations in sub-slab samples and indoor air samples was generally similar over the two rounds of testing. Specifically, the change in COC concentrations in indoor air between the negative pressure condition and the positive pressure condition was the same between the two rounds. As a result, the interpretation of the results for the sources of the detected chemicals (i.e., above ground vs. subsurface) is the same for the two rounds. This demonstration of reproducibility increases confidence that the investigation procedure provides reliable results.

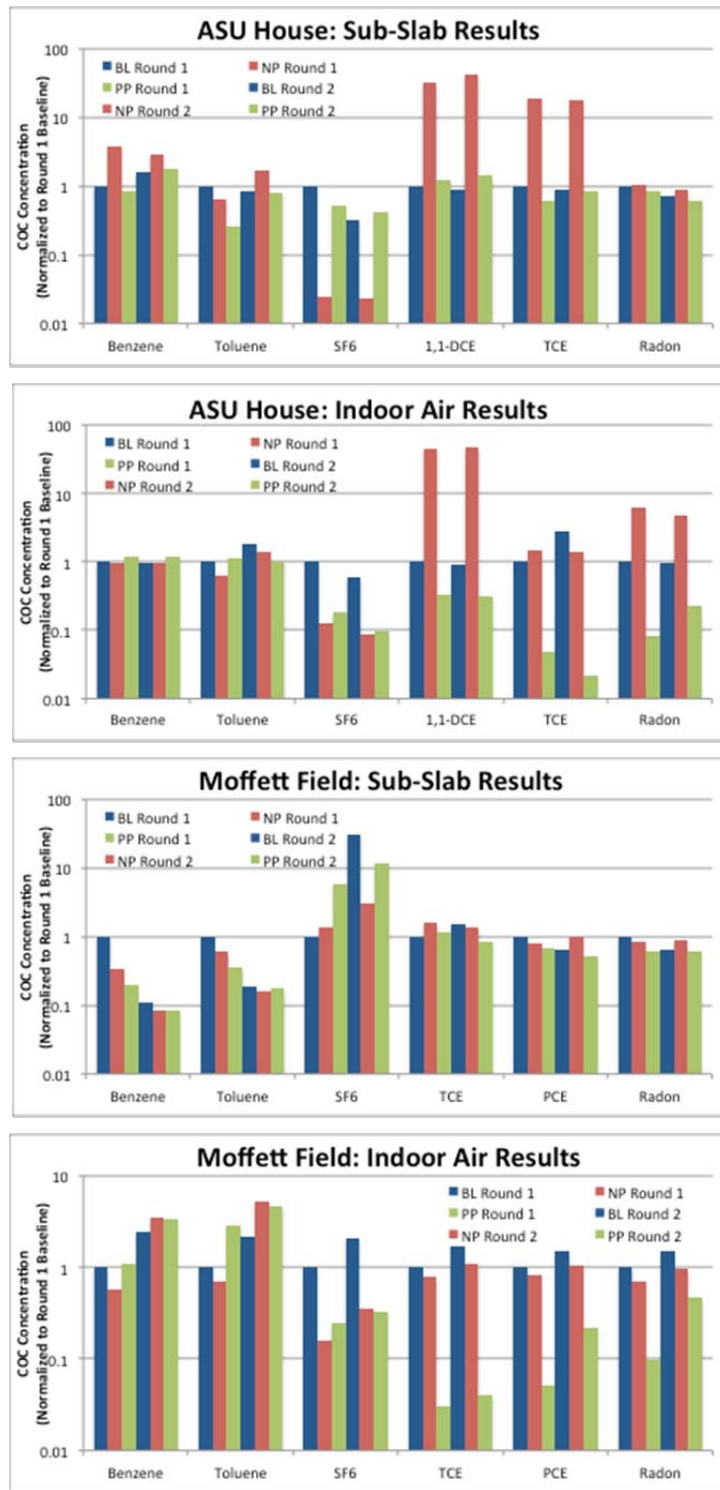


Figure 47. Comparison of concentration results during two rounds of testing.

6.3.3.2 Control of Temporal Variability in Vapor Intrusion

A relatively recent concern is temporal variability in vapor intrusion. For some buildings (e.g., ASU Research House, Hill AFB), vapor intrusion is episodic. For this type of building, a single standard testing event may not accurately identify a true VI problem. As a result, several standard testing events may be required to confirm an absence of vapor intrusion.

The demonstration dataset indicates that building depressurization can be used to evaluate the potential for episodic vapor intrusion during a single testing event. For the ASU Research House, the baseline sampling results showed an absence of VI during this testing event. However, the sample results from the controlled negative pressure condition showed clear VI, indicating a potential for VI to occur under some building operating conditions. At a less well-characterized building, additional investigation would be required to evaluate whether VI would occur under any actual building operating conditions. However, the results from the controlled negative pressure condition would flag the building as high priority for additional investigation. In contrast, an absence of VI under controlled negative pressure conditions would provide a high level of confidence that there is little to no potential for episodic vapor intrusion.

6.3.3.3 Limitations of Sub-Slab Samples for Evaluation of Vapor Intrusion

The current standard building-specific vapor intrusion sampling program uses indoor air and sub-slab sample results to evaluate the presence or absence of VI using a multiple lines of evidence data evaluation approach (ITRC, 2007). A key line of evidence is the detection of COCs in sub-slab samples at concentrations at least 10 times those detected in indoor air. Based on the dilution that occurs between the subsurface and indoor air, vapor intrusion is considered unlikely to result in COC concentrations in indoor air that are greater than 10% of the sub-slab concentrations. Higher than expected concentrations of COCs in indoor air is considered strong evidence that indoor or ambient sources are contributing to the concentrations in indoor air.

The demonstration dataset illustrates the limitations of this line of evidence for evaluating vapor intrusion. At Moffett Field Building 107, the sub-slab concentrations of TCE and PCE were similar to the indoor air concentration during all three test conditions (baseline, negative pressure, and positive pressure) while the radon concentrations were 500 to 1000 times higher than in indoor air. Using the standard lines of evidence approach, this would be considered strong evidence of an indoor source of TCE and PCE. However, the results from the controlled negative and positive pressure test conditions clearly showed that TCE, PCE, and radon all originated from subsurface sources (i.e., the concentrations of all three COCs were elevated in indoor air during the negative pressure condition but equal to ambient concentrations under the positive pressure condition).

6.3.4 Summary of Validation of Pressure Control Investigation Procedure

The demonstration in six buildings has led to the validation of the Pressure Control Investigation procedure:

- ANOVA conducted on the entire demonstration dataset shows that the control of building pressure provides the ability to distinguish between COCs originating from subsurface sources vs. COCs originating from above-ground sources based on the change in concentration in indoor air between the controlled negative pressure condition and the controlled positive pressure condition ($p = 0.03$).

- For the six demonstration buildings, the change in COC concentration in indoor air between the controlled negative pressure condition and the controlled positive pressure condition matched the predicted change for subsurface COCs (i.e., decrease in concentration) for 17 of 19 cases, and matched the predicted change for above-ground COCs (i.e., no change or change matching the change in ambient concentrations) in 16 of 20 cases.

Some of the specific hypotheses were not validated:

- The changes in COC concentration in sub-slab samples did not generally match the prediction.
- There was no clear correlation between measured foundation permeability and the magnitude of vapor intrusion in the six demonstration buildings.

The validation dataset supports some additional findings not discussed in the original demonstration plan:

- Implementation of the investigation procedure twice in each of two demonstration buildings showed that the procedure yields reproducible results.
- The Pressure Control Investigation procedure can be used to control for temporal variability in buildings with episodic vapor intrusion (e.g., Hill AFB ASU Research House).
- The investigation procedure can be used to accurately identify vapor intrusion in buildings where the standard lines of evidence approach would incorrectly suggest an indoor source (e.g., Moffett Field Building 107).

6.4 PRESSURE CONTROL INVESTIGATION PROCEDURE

The goal of the field demonstration was to produce a validated procedure for a streamlined building investigation program that provides a reliable determination of the presence or absence of a VI concern for that building. The actual investigation procedure is less extensive than the program implemented to validate the procedure. For the validation, additional data were required to fully evaluate the procedure performance. The streamlined evaluation procedure consists of procedures for (1) control of building pressure to create negative and positive building pressure conditions, (2) a VOC and tracer gas sampling program, (3) pressure gradient measurements, and (4) data interpretation methods.

6.4.1 Overview of Pressure Control Investigation Procedure

Conceptually, sampling of indoor air is the most direct method to evaluate the presence or absence of vapor intrusion at a specific building. However, sampling of indoor air during a single sampling event has two key limitations: (1) the sampling event might not be scheduled during “worst-case” VI conditions when flow of soil gas into the building is maximized, and (2) VOCs detected in indoor air samples cannot easily be attributed to a specific source (i.e., vapor intrusion or an indoor source). Currently, some state regulatory guidance documents recommend multiple indoor sampling events or building sampling only during specific weather conditions (i.e., during the heating seasons) to characterize “worst-case” VI conditions (Indiana Department of Environmental Management, 2012; Montana Department of Environmental Quality, 2011; New Jersey Department of Environmental Protection, 2012; North Carolina Department of Environmental and Natural Resources, 2011; Washington Department of Ecology, 2009). In addition, most regulatory guidance documents recommend use of “multiple lines of evidence” to distinguish between vapor intrusion and indoor sources of VOCs.

For buildings with concrete foundations, the streamlined building sampling procedure uses the manipulation of building pressure to “turn on” and “turn off” vapor intrusion (see Figure 48). Indoor air samples collected under controlled negative building pressure conditions are used to characterize indoor air quality under conditions of maximum soil gas entry into the building while indoor air samples collected under controlled positive pressure building conditions are used to characterize indoor air quality in the absence of soil gas entry. As a result, VOCs detected in indoor air under positive building pressure conditions are generally representative of sources other than VI. During a single 3-day sampling event, this streamlined evaluation procedure documents indoor air quality under a range of building pressure conditions allowing the determination of the impact of vapor intrusion and other VOC sources on indoor air quality.

6.4.2 Pressure Control Investigation Procedure

6.4.2.1 Sampling Program

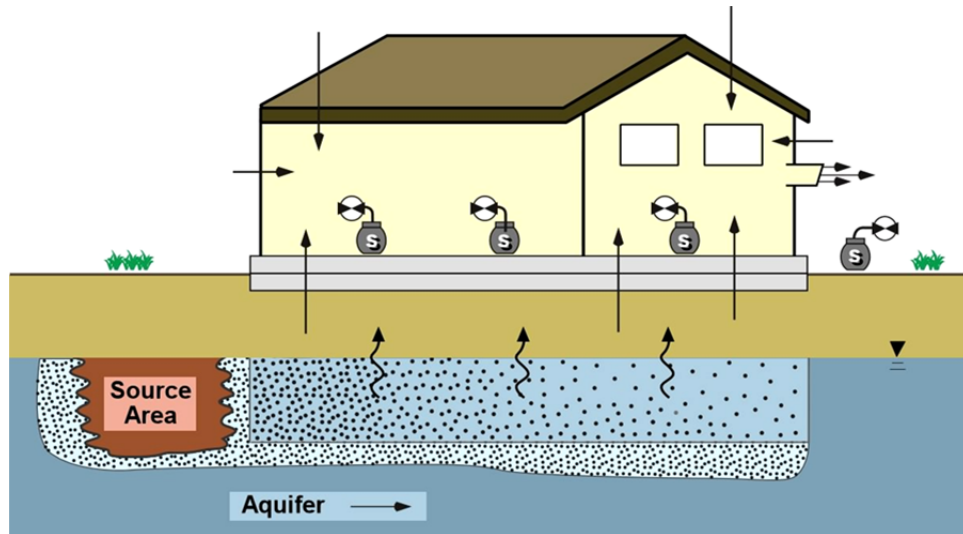
The pressure control method requires measurement of indoor and ambient radon concentrations under baseline conditions and indoor and ambient radon and VOC concentrations under negative building pressure conditions and positive building pressure conditions over a 3-day period (see Table 25 and Figure 49).

6.4.2.2 Data Interpretation

The magnitude of vapor intrusion in the building is evaluated by comparing the VOC concentration in indoor air measured under negative building pressure to the VOC concentration in indoor air measured under positive building pressure conditions. The difference in VOC concentration between the two test conditions is the VOC concentration attributable to vapor intrusion. For example, if the concentration of PCE in indoor air is $5 \mu\text{g m}^{-3}$ under negative building pressure conditions, and $1 \mu\text{g m}^{-3}$ under positive building pressure conditions, then the PCE in indoor air under negative pressure conditions is primarily attributable to vapor intrusion. Based on the variability typically observed between the indoor air measurement locations, the resulting dataset is usually not suitable for a quantitative determination of impact of VI (i.e., for the PCE example, an estimate that 80% of the PCE in indoor is attributable to VI would have a large uncertainty). However, the resulting dataset is usually sufficient for identifying the primary source of each COC in indoor air).

The radon results are used as a positive control tracer for the movement of soil gas into the building. Although radon concentrations in soil gas are higher in some regions than in others, the radon concentration in sub-slab soil gas is typically high enough to be used as a tracer for the movement of soil gas through the building foundation (i.e., radon concentration in soil gas is typically $> 100 \text{ pCi L}^{-1}$). As a result, when soil gas is entering the building through the building foundation, the concentration in indoor air will be higher than the concentration in ambient air. Thus, the radon results will be used to verify that soil gas entry into the building is occurring under negative pressure conditions and eliminated under positive pressure conditions. The interpretation of the radon results is provided in Table 26.

Controlled
negative
building
pressure:
Vapor
intrusion is
“on”



Controlled
positive
building
pressure:
Vapor
intrusion is
“off”

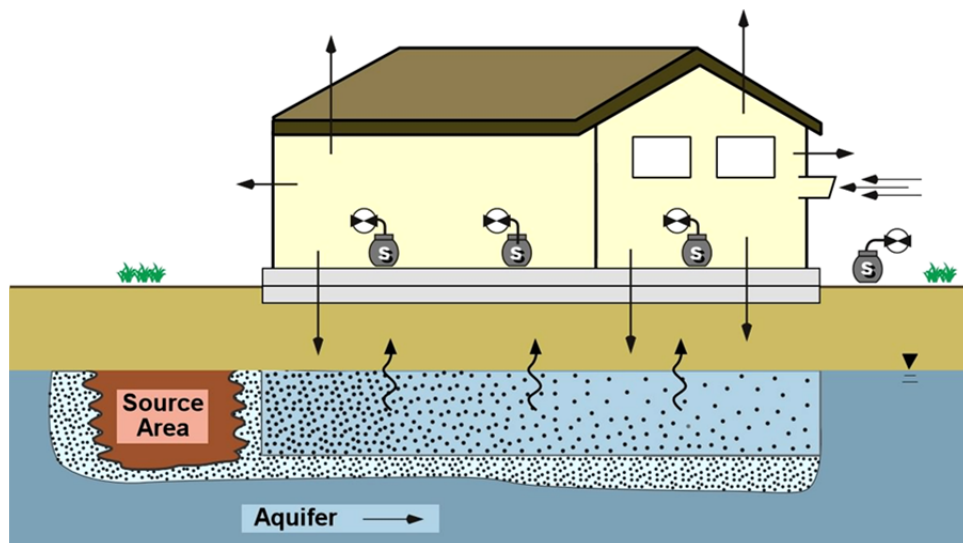


Figure 48. Conceptual illustration of building pressure control for the building-specific evaluation of vapor intrusion.

Table 25. Pressure control method sampling program: routine application.

Pressure Condition	Matrix	Number of Samples	Analyte	Location
Baseline	Indoor air	1	Radon	Open area on lowest building level
Negative Pressure	Indoor air	1 to 3	Radon, VOCs	Open area on lowest building level plus up to two additional samples based on building layout
	Ambient air	1	Radon, VOCs	Upwind location
Positive Pressure	Indoor air	1 to 3	Radon, VOCs	Open area on lowest building level plus up to two additional samples based on building layout
	Ambient air	1	Radon, VOCs	Upwind location

Method	Day 1	Day 2	Day 3
1. Baseline sampling			
2. Building depressurization (12-hour equilibration and 8-hr sampling)			
3. Collection of depressurization samples			
4. Building pressurization (12-hour equilibration and 8-hr sampling)			
5. Collection of pressurization samples			

Figure 49. Pressure control method field schedule: routine application.

Table 26. Use of radon concentration data to verify method performance.

Comparison	Condition	Interpretation
Radon concentration in indoor air: baseline vs. negative pressure	Baseline concentration \leq negative pressure condition	Negative pressure condition has maximized vapor intrusion
	Baseline concentration $>$ negative pressure condition	Increased air exchange associated with building depressurization may have caused dilution of vapor intrusion impact
Radon concentration under positive pressure: indoor vs. ambient	Concentration in indoor air = concentration in ambient air	Positive pressure condition has "turned off" vapor intrusion
	Concentration in indoor air $>$ concentration in ambient air	Some vapor intrusion may be occurring under positive pressure conditions

7. COST ASSESSMENT

7.1 COSTS ASSOCIATED WITH PASSIVE SAMPLERS

This section presents the results of a cost assessment to implement site investigation and monitoring using passive samplers. Section 7.1.1 describes a cost model that was developed for different scenarios for site investigation and monitoring using passive samplers and an analysis of the cost model; Section 7.1.2 presents an assessment of the cost drivers for the application of passive samplers.

7.1.1 Cost Scenario 1 for Passive Samplers

A cost model was developed to assist remediation professionals in understanding costs associated with passive sampling versus active sampling. The cost model is easiest to understand when compared to active sampling, since the main differences are in field technician time. The cost model identified the major cost elements required to implement passive sampling under three different scenarios.

The cost model was developed for the following scenarios:

- Scenario 1 – collection of seven (7) sub-slab soil gas samples, seven (7) indoor air samples, and two (2) outdoor air samples at a single building (Table 27).
- Scenario 2 – collection of fifty (50) sub-slab soil gas samples, fifty (50) indoor air samples, and twelve (12) outdoor air samples at several large buildings (Table 28).
- Scenario 3 – a contaminated groundwater plume is migrating beneath a residential community adjacent to a DoD facility. Soil gas probes are installed and sampled to map the subsurface vapor distribution (approximately 100 samples) and the indoor and sub-slab samples are collected in buildings over the areas of elevated soil vapor concentrations (approximately 50 each). Two rounds of sampling are conducted to assess seasonal variations. This scenario assumes that the building occupants are cooperative and willing to watch the passive sampling collection procedures during the first sampling event and deploy their own indoor air and outdoor air samples during the second sampling event (much as is the case with many radon samplers in domestic applications) (Table 29).

The cost of using passive samplers in the above scenarios is similar to or less than the cost of using active samplers, as shown in Table 27, Table 28 and Table 29.

Table 27. Costs associated with conventional active and passive samplers for Cost Scenario 1. The first cost scenario consists of the collection of seven sub-slab soil gas samples (6 samples and 1 duplicate), seven (7) indoor air samples (6 samples and 1 duplicate), and two (2) outdoor air samples at a single building. The cost comparison between the five passive and one active Summa™ canister sampler are provided below.

Item	Unit Cost	Unit	Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC		
			Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	
LABOR COSTS																	
Active (Conventional Summa/TO-15)																	
Laboratory coordination, planning	\$125	hour	2	2	\$250	\$250											
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	4		\$340												
Sub-slab sample collection (deployment and retrieval)	\$85	hour		9		\$765											
Soil gas sample collection (deployment and retrieval)	\$85	hour															
Passive		hour															
Laboratory coordination, planning	\$125	hour	4	4			\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	4				\$340		\$340		\$340		\$340		\$340		
Sub-slab sample collection (deployment and retrieval)	\$85	hour		3				\$255		\$255		\$255			\$255	\$255	
Soil gas sample collection (deployment and retrieval)	\$85	hour															
LABORATORY COSTS*																	
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	\$20	each		8		\$160											
Flow Controller (100 mL/min for soil gas/sub-slab)	\$15	each		8		\$120											
Modified EPA TO-15 (open scan for soil gas/subslab)	\$140	each		8		\$1,120											
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	\$30	each	9		\$270												
Flow controller (24 hr for indoor/outdoor air)	\$10	each	9		\$90												
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	\$180	each	9		\$1,620												
WMSTM Sampler	\$25	each	10	8			\$0	\$200									
WMSTM Analysis (solvent extraction for soil gas/sub-slab)	\$150	each		8				\$1,200									
WMSTM Analysis (thermal desorption for indoor/outdoor air)	\$200	each	10				\$2,000										
Radiello Sampler	\$30	each	10	8					\$300	\$240							
Radiello Analysis (modified EPA TO-17)	\$150	each	10	8					\$1,500	\$1,200							
ATD Tube	\$30	each	10	8							\$300	\$240					
ATD Tube Analysis (modified EPA TO-17)	\$200	each	10	8							\$2,000	\$1,600					
3M OVM 3500 Badge	\$20	each	10	8									\$200	\$160			
3M OVM 3500 Badge Analysis	\$150	each	10	8									\$1,500	\$1,200			
SKC Ultra II Sampler	\$75	each	10	8											\$750	\$600	
SKC Ultra II Sampler Analysis (modified EPA TO-17)	\$200	each	10	8											\$2,000	\$1,600	
EXPENSES																	
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	\$950	shipment	9		\$534												
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	\$238	shipment		8		\$119											
Federal Express (Standard Overnight) - 16 passive samplers	\$60	shipment	10	8			\$38	\$30	\$38	\$30	\$38	\$30	\$38	\$30	\$38	\$30	
Concrete coring contractor (SKC and OVM only)	\$500	day		1										\$500		\$500	
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	\$200	sweek		1		\$200		\$200		\$200		\$200					
Helium detector	\$350	week		1		\$350											
Helium cylinder	\$150	each		1		\$150											
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	\$25	each		6		\$150											
1 inch rubber stoppers, aluminum foil and Teflon tape (passive sampling)	\$1	each		6				\$6		\$6		\$6		\$6		\$6	
Soil gas probe materials (passive)	\$25	each															
Soil gas probe materials (active)	\$50	each															
Subtotal						\$3,104	\$3,384	\$2,878	\$2,391	\$2,678	\$2,431	\$3,178	\$2,831	\$2,578	\$2,651	\$3,628	\$3,491
TOTAL						\$6,488		\$5,269		\$5,109		\$6,009		\$5,229		\$7,119	

Note: passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

Table 28. Costs associated with conventional active Summa™ canister and five different passive samplers for Cost Scenario 2. This scenario includes the collection of fifty (50) sub-slab soil gas samples, fifty (50) indoor air samples, and twelve (12) outdoor air samples.

Item	Unit Cost	Unit	Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC	
			Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab
LABOR COSTS																
Active (Conventional Summa/TO-15)																
Laboratory coordination, planning	\$125	hour	2	2	\$250	\$250										
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	29		\$2,465											
Sub-slab sample collection (deployment and retrieval)	\$85	hour		75		\$6,375										
Soil gas sample collection (deployment and retrieval)	\$85	hour														
Passive		hour														
Laboratory coordination, planning	\$125	hour	4	4			\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	29				\$2,465		\$2,465		\$2,465		\$2,465		\$2,465	
Sub-slab sample collection (deployment and retrieval)	\$85	hour		25				\$2,125		\$2,125		\$2,125		\$2,125		\$2,125
Soil gas sample collection (deployment and retrieval)	\$85	hour														
LABORATORY COSTS*																
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	\$20	each		50		\$1,000										
Flow Controller (100 mL/min for soil gas/sub-slab)	\$15	each		50		\$750										
Modified EPA TO-15 (open scan for soil gas/subslab)	\$140	each		50		\$7,000										
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	\$30	each	62		\$1,860											
Flow controller (24 hr for indoor/outdoor air)	\$10	each	62		\$620											
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	\$180	each	62		\$11,160											
WMS™ Sampler	\$25	each	63	51			\$0	\$1,275								
WMS™ Analysis (solvent extraction for soil gas/sub-slab)	\$150	each		51				\$7,650								
WMS™ Analysis (thermal desorption for indoor/outdoor air)	\$200	each	63				\$12,600									
Radiello Sampler	\$30	each	63	51					\$1,890	\$1,530						
Radiello Analysis (modified EPA TO-17)	\$150	each	63	51					\$9,450	\$7,650						
ATD Tube	\$30	each	63	51							\$1,890	\$1,530				
ATD Tube Analysis (modified EPA TO-17)	\$200	each	63	51							\$12,600	\$10,200				
3M OVM 3500 Badge	\$20	each	63	51									\$1,260	\$1,020		
3M OVM 3500 Badge Analysis	\$150	each	63	51									\$9,450	\$7,650		
SKC Ultra II Sampler	\$75	each	63	51											\$4,725	\$3,825
SKC Ultra II Sampler Analysis (modified EPA TO-17)	\$200	each	63	51											\$12,600	\$10,200
EXPENSES																
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	\$950	shipment	62		\$3,681											
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	\$238	shipment		50		\$742										
Federal Express (Standard Overnight) - 16 passive samplers	\$60	shipment	63	51			\$236	\$191	\$236	\$191	\$236	\$191	\$236	\$191	\$236	\$191
Concrete coring contractor (SKC and OVM only)	\$500	day		2										\$1,000		\$1,000
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	\$200	sweek		2		\$400		\$400		\$400		\$400				
Helium detector	\$350	week		2		\$700										
Helium cylinder	\$150	each		7		\$1,050										
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	\$25	each		50		\$1,250										
1 inch rubber stoppers, aluminum foil and Teflon tape (passive sampling)	\$1	each		50				\$50		\$50		\$50		\$50		\$50
Soil gas probe materials (passive)	\$25	each														
Soil gas probe materials (active)	\$50	each														
Subtotal					\$20,036	\$19,517	\$15,801	\$12,191	\$14,541	\$12,446	\$17,691	\$14,996	\$13,911	\$12,536	\$20,526	\$17,891
TOTAL					\$39,553	\$27,993	\$26,988		\$32,688		\$26,448		\$38,418			

Note: passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

Table 29. Costs associated with conventional active Summa™ canister and passive samplers for Cost Scenario 3.

Item	Unit Cost	Unit	Number of Units		Conventional Summa/TO-15		WMS		Radiello		ATD		OVM		SKC	
			Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab	Indoor & Outdoor	Sub-slab
LABOR COSTS																
Active (Conventional Summa/TO-15)																
Laboratory coordination, planning	\$125	hour	2	2	\$250	\$250										
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	50		\$4,250											
Sub-slab sample collection (deployment and retrieval)	\$85	hour		150		\$12,750										
Soil gas sample collection (deployment and retrieval)	\$85	hour		450		\$38,250										
Passive																
Laboratory coordination, planning	\$125	hour	4	4			\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500	\$500
Indoor and outdoor sample collection (deployment and retrieval)	\$85	hour	35				\$2,975		\$2,975		\$2,975		\$2,975		\$2,975	
Sub-slab sample collection (deployment and retrieval)	\$85	hour		50				\$4,250		\$4,250		\$4,250		\$4,250		\$4,250
Soil gas sample collection (deployment and retrieval)	\$85	hour		250				\$21,250		\$21,250		\$21,250		\$21,250		\$21,250
LABORATORY COSTS*																
1 Liter Summa Canister (Batch Certified for soil gas/sub-slab)	\$20	each		300		\$6,000										
Flow Controller (100 mL/min for soil gas/sub-slab)	\$15	each		300		\$4,500										
Modified EPA TO-15 (open scan for soil gas/subslab)	\$140	each		300		\$42,000										
6 Liter Summa Canister (Individually Certified for indoor/outdoor air)	\$30	each	100		\$3,000											
Flow controller (24 hr for indoor/outdoor air)	\$10	each	100		\$1,000											
Modified EPA TO-15 SIM and scan (for indoor/outdoor air)	\$180	each	100		\$18,000											
WMS™ Sampler	\$25	each	100	300			\$0	\$7,500								
WMS™ Analysis (solvent extraction for soil gas/sub-slab)	\$150	each		300				\$45,000								
WMS™ Analysis (thermal desorption for indoor/outdoor air)	\$200	each	100				\$20,000									
Radiello Sampler	\$30	each	100	300					\$3,000	\$9,000						
Radiello Analysis (modified EPA TO-17)	\$150	each	100	300					\$15,000	\$45,000						
ATD Tube	\$30	each	100	300							\$3,000	\$9,000				
ATD Tube Analysis (modified EPA TO-17)	\$200	each	100	300							\$20,000	\$60,000				
3M OVM 3500 Badge	\$20	each	100	300									\$2,000	\$6,000		
3M OVM 3500 Badge Analysis	\$150	each	100	300									\$15,000	\$45,000		
SKC Ultra II Sampler	\$75	each	100	300											\$7,500	\$22,500
SKC Ultra II Sampler Analysis (modified EPA TO-17)	\$200	each	100	300											\$20,000	\$60,000
EXPENSES																
Federal Express (Standard Overnight) - 16 Summa canisters (6L)	\$950	shipment	100		\$5,938											
Federal Express (Standard Overnight) - 16 Summa canisters (1L)	\$238	shipment		300		\$4,453										
Federal Express (Standard Overnight) - 16 passive samplers	\$60	shipment	100	300			\$375	\$1,125	\$375	\$1,125	\$375	\$1,125	\$375	\$1,125	\$375	\$1,125
Concrete coring contractor (SKC and OVM only)	\$500	day		10										\$5,000		\$5,000
Hammer drill (conventional Summa, WMS, Radiello and ATD only)	\$200	sweek		4		\$800		\$800		\$800		\$800				
Helium detector	\$350	week		7		\$2,450										
Helium cylinder	\$150	each		37		\$5,550										
Sub-slab probe parts (stainless steel) (conventional Summa sampling)	\$25	each		50		\$1,250										
1 inch rubber stoppers, aluminu	\$1	each		50				\$50		\$50		\$50		\$50		\$50
Soil gas probe materials (passive)	\$25	each		100				\$2,500		\$2,500		\$2,500		\$2,500		\$2,500
Soil gas probe materials (active)	\$50	each		100		\$5,000										
Subtotal					\$32,438	\$123,253	\$23,850	\$82,975	\$21,850	\$84,475	\$26,850	\$99,475	\$20,850	\$85,675	\$31,350	\$117,175
TOTAL					\$155,691		\$106,825		\$106,325		\$126,325		\$106,525		\$148,525	

Note: passive sampler laboratory analytical costs assume an analyte list of 20 compounds or less.

7.1.2 Cost Drivers for Passive Samplers

Passive samplers can reduce costs because the protocols for sampling are simpler, and as a result the costs of training and labor for field personnel are lower than in conventional sampling methods. The passive samplers are also smaller and lighter than Summa canisters, so shipping costs are lower. Passive samplers are also capable of collecting samples over a longer period of time than conventional samplers, so fewer samples may be needed to provide data over a given period.

Passive samplers incur more effort in the initial design process because it takes time to select the best sampler, sorbent and exposure duration for a given set of target chemicals and target reporting limits. This process can be automated to a significant degree, but should be reviewed by an experienced analytical chemist. Inter-method verification samples are a valuable quality assurance/quality control element that allows uptake rates to be derived or verified for site-specific field sampling conditions, which would add a small increment to the overall cost for sampling campaigns, but add a level of quality control and assurance where the highest level of accuracy is desired.

The cost differential between the various types of passive samplers is relatively small, so the selection between the passive sampling options should be based primarily on technical considerations. One exception is if sub-slab sampling is included, because the larger diameter of the SKC and OVM samplers would require a larger diameter hole, and the cost of coring is higher than the cost of using a hammer-drill to make a smaller diameter hole sufficient to accommodate the ATD, Radiello, or WMS samplers.

7.2 COSTS ASSOCIATED WITH BUILDING PRESSURE CONTROL

The Building Pressure Control Investigation procedure is fundamentally a site characterization method. As such, key cost components for the method are (1) sample point installation, (2) sample collection and analysis, and (3) data analysis and reporting (McHugh, Beckley, and Baily, 2012b).

7.2.1 Cost Drivers

The cost for implementing the Building Pressure Control Investigation procedure is not expected to vary significantly based on specific site characteristics. This is because the Building Pressure Control Investigation procedure uses a fixed sampling program that will not vary based on site-specific characteristics.

7.2.2 Cost Analysis

The cost estimates for implementing the building pressure control investigation procedure assume implementation by experienced personnel. For any procedure or field program, the time required for the first implementation by inexperienced personnel would be significantly higher.

7.2.3 Operational Implementation Costs for the Building Pressure Control Investigation Procedure

The Building Pressure Control Investigation procedure involves manipulating building pressure and collecting air samples during three different pressure conditions: baseline, negative pressure, and positive pressure. Estimated costs to implement this investigation procedure are shown in Table 31. The sampling itself takes place over the course of three days, with 4 to 6 hours per day for each of two persons assumed for equipment checks, setup, and pickup.

Table 30. Costs for routine implementation of the Building Pressure Control Investigation procedure.

Cost Element	Cost Category	Description	Number of units	Unit	Unit Cost (\$)	Cost (\$)	Subtotal (\$)
Project planning and preparation ¹	Labor	Senior project scientist/engineer	4	hours	150	600	1,200
	Labor	Project scientist / engineer	6	hours	100	600	
Pressure control and sampling field program	Labor	Senior project scientist/engineer	16	hours	150	2400	6,235
	Labor	Project scientist / engineer	16	hours	100	1600	
	Equipment rental	Floor fan, differential pressure recorder	1	per building	225	225	
	Sample analysis	VOCs (four samples + one field duplicate)	5	samples	270	1350	
	Sample analysis	Radon (five samples + one field duplicate)	6	samples	110	660	
Data evaluation and reporting ¹	Labor	Senior project scientist/engineer	4	hours	150	600	1,200
	Labor	Project scientist / engineer	6	hours	100	600	
PROJECT TOTAL:							\$8,635

Note: 1) Estimates for project planning (Task 1) and (Task 3) are the per-building cost assuming application of the procedure at four or more buildings during a single field program. The per-building costs would be larger if applied to only one to three buildings.

2) Cost estimates do not include travel to the site. The actual number of samples will depend on the building configuration.

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14. ABSTRACT <p>This report includes findings and results from the demonstration of passive samplers and building pressure control in eight Department of Defense (DoD) sites. Due to the nature of the methods, as well as to programmatic factors, researchers were unable to demonstrate both methods at all of the sites, and some of the sites were only tested with one of the two methods. However, the experience and recommendations developed from these demonstrations is applicable to many other DoD and industrial sites in general. Navy site managers and the public can use this technical report to apply passive samplers and/or build pressure control supporting improved VI assessment by following methodology proved in this effort, which is available to the regulatory and scientific communities, as well as to the general user. The recommendations specifically provide direction on the collection of indoor air and soil gas samples supporting vapor intrusion assessment. This "top-down" approach should provide the appropriate information required to support "No Further Action" at sites eligible for such action. The potential for return on investment for this project is significant because it can provide a basis for continued research and provide cost-effective, accepted solutions to support effective vapor intrusion assessment.</p> <p>The results from these demonstrations attest to the capability of passive samplers and building pressure control for assessment of vapor intrusion. These demonstrations provided information of the use of passive samplers for long-term quantification of VOCs. They also provided the knowledge for correct use of passive samplers under a suite of conditions. Similarly, it was demonstrated that building pressure control could assess indoor sources, VI, and the worst-case scenario for positive vapor intrusion. Applying these top-down approaches should streamline initial, and ongoing, assessment of VI, and should provide the evidence required for "No Further Action" when that condition is endorsed.</p>					
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