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For Open Publication

Aug 20, 2019

Department of Defense
OFFICE OF PREPUBLICATION AND SECURITY REVIEW

DoD Vapor Intrusion Handbook
Fact Sheet Update No: 007
Date: July 2019

Matrix for Selecting Vapor Intrusion Investigation Technologies

Purpose

The purpose of this fact sheet is to provide Remedial Project Managers (RPMs) with a matrix that facilitates selection of the most effective technologies for investigating the vapor intrusion (VI) pathway at Department of Defense (DoD) facilities with identified subsurface chlorinated volatile organic compound (CVOC) contamination.[1] The matrix is based on a generalized VI pathway conceptual site model (CSM) (see **Figure 1**) and is organized by investigation objectives (rows in **Table 1**) and technology categories (columns in **Table 1**).

The investigation objectives follow a "bottom up" approach, from characterization of subsurface sources, through evaluation of vadose zone vapor migration pathways, to investigation of a building's sub-slab region and interior. However, assessment of the VI pathway can begin at any point in the pathway, depending on site-specific conditions and RPM preferences. The technologies are ranked to facilitate selection of the most effective technologies to address the stated objectives. RPMs are encouraged to engage a qualified team of environmental professionals to assist with developing site-specific VI assessment plans.

The information and references in this fact sheet are generally applicable to all existing building types and exposure scenarios (industrial/commercial and residential). However, individual building characteristics vary and are an important consideration when selecting investigation technologies. The matrix also identifies technologies applicable to evaluation of potential VI impacts in future construction. The information in this fact sheet provides general guidance and is not intended to replace expert knowledge and judgment.

Introduction

VI is the migration of volatile chemicals from subsurface sources into the indoor air of overlying or nearby buildings.

Assessment of the VI pathway is complex because of the dynamic nature of subsurface, building, and atmospheric transport processes, which can lead to temporal and spatial variability of chemical concentrations. Numerous investigative tools have been developed to address these complexities. The effectiveness of these tools to address investigation objectives depends on site conditions as well as the accuracy and comprehensiveness of the CSM.

The Navy Environmental Sustainable Development to Integration (NESDI) Program's VI Quantitative Decision Framework (QDF) is a useful reference for identifying and prioritizing industrial buildings for VI investigations (Naval Facilities Engineering Command [NAVFAC], 2015). In addition, the Navy is in the process of developing a Quality Assurance Project Plan (QAPP) template for VI investigations.

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[1] This fact sheet assumes that existing groundwater and/or bulk soil sampling results indicate VOC/semi-volatile organic compound (SVOC) contamination in the subsurface and that the potential for VI to impact current or future buildings at the facility needs investigation. Therefore, the matrix does not include technologies for sampling groundwater or bulk soil for chemical analysis.

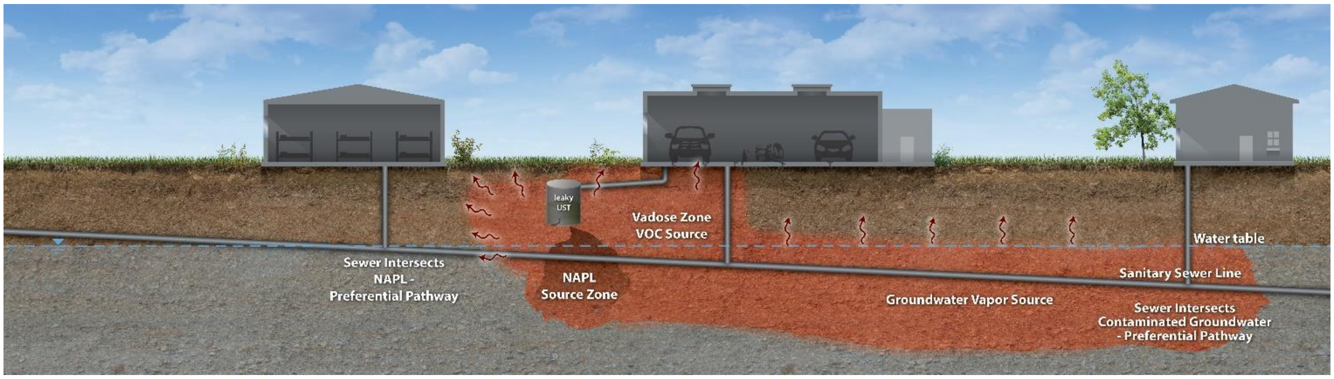
Vapor Intrusion Conceptual Site Model

The VI CSM (see **Figure 1**) is generally depicted as a vertical cross section of a vapor source underlying or situated near a building. Vapor sources may include volatile or semi-volatile compounds adsorbed to soil, dissolved in groundwater, in non-aqueous phase liquids (NAPLs), or a combination of these sources. Vapors emitted from the source typically move through porous materials in the vadose zone via diffusion and are drawn across the building foundation through cracks and openings in the building envelope by a combination of diffusion and advection. Advective transport generally is more important close to the building and through open subsurface pathways, such as utility conduits, that have low resistance to flow and that intercept the vapor source (McHugh, 2017). A general VI CSM is useful for visualizing the VI pathway, but additional information is often needed to determine whether the VI pathway is complete and could potentially pose unacceptable risk as defined by the regulatory program.

In general, the strength of subsurface vapors relative to their VI potential decreases with increasing distance from the building (existing or future). The distance at which subsurface concentrations become insignificant varies based on several factors such as source type, size and location of vapor source, soil types, ground cover, and presence of preferential pathways. To identify which existing or future buildings to further evaluate, regulatory guidance generally recommends evaluating buildings within approximately 100 feet (chlorinated compounds) or 30 feet (petroleum compounds) laterally from the boundary of measured and/or inferred subsurface VOC concentrations that exceed vapor intrusion screening levels (VISLs). These distances may be greater or less depending on site-specific and are referred to as the inclusion zone. The inclusion zone may be greater at sites where preferential pathways intercept the vapor source area and provide little resistance to vapor flow (**Figure 1**).

The VI pathway is deemed incomplete if VOCs present in subsurface sources are not detected in indoor air. Conversely, the VI pathway is deemed complete if VOCs present in subsurface sources are detected in indoor air and the VOCs are deemed to be due to VI (i.e., there are no significant contributions from background indoor or outdoor sources). If the VI pathway is complete and poses an unacceptable health risk, actions to remediate subsurface sources generally will be needed. If VOCs from subsurface sources are detected in sub-slab soil gas above screening levels but are not detected in indoor air or are at levels below risk-based targets, the VI pathway may be considered to pose a potential risk due to the potential for future slab penetrations or changes to the building structure and actions to remediate subsurface sources may be considered or recommended.

Figure 1. Example VI CSM Scenario - Vapor Intrusion Matrix of Technologies for Selecting the Most Effective Investigative Strategies



Matrix of Vapor Intrusion Technologies

VI investigation technologies that can be used to characterize the VI pathway and determine whether the pathway is complete are identified and ranked in **Table 1**. These technologies are categorized under soil screening, soil vapor and indoor air field screening methods, soil vapor and indoor air sampling methods, and forensic tools. The forensic tools may include soil vapor and/or air sampling for chemical analysis by the methods described in the matrix, but also include collection of other chemical and/or physical data and use advanced means of data evaluation. The technologies are ranked according to their effectiveness for addressing common VI investigation objectives, including:

- Characterizing near source vapor concentrations;
- Identifying vapor migration pathways;
- Identifying points of vapor entry through the building foundation;
- Characterizing building conditions that influence VI;
- Characterizing temporal and spatial variability of indoor air concentrations;
- Identifying background sources; and
- Developing reasonable maximum exposure concentrations for long-term and short-term risk assessment.

Technologies that address the first two objectives above are relevant to evaluation of future potential VI risk in areas where construction is planned or is possible. The remainder of the investigation objectives apply only to existing buildings.

Most regulatory agencies generally require indoor air sample collection via evacuated canisters (TO-15) or active sorbent tubes (TO-17) for analysis by accredited laboratories for decision-making based on indoor air exposure concentrations. However, the screening and forensic methods included in the matrix can be used to optimize times and locations for indoor air sampling and provide additional lines of evidence that can greatly increase the confidence in risk management decisions. When designing sampling programs, it is important to consider whether the sampling results will be used to evaluate acute exposures, chronic exposures or for diagnostic purposes. Sampling numbers and duration will also vary depending on building size, contaminant types, and residential versus non-residential building use.

Technology rankings indicate the following:

-	Not applicable or expected to perform poorly
+	Provides some information when combined with other higher ranked technologies
++	Useful technology for the stated objective
+++	Provides most definitive results or represents state-of-the-art technology

The technology rankings were assigned using expert judgment primarily based on their technical merit. However, two rows at the bottom of the Table 1 rank the relative cost and time required to implement the technologies and Table 2 provides notes regarding quality, cost, time and synergistic combinations for each technology. Additionally, the technologies listed in Table 1 generally are not implemented as standalone approaches to VI assessment. They generally are implemented in combinations tailored to specific scenarios. The last row of Table 1 provides cross-references for complementary technologies commonly used in combination.

The evidence obtained through application of the listed technologies should be used to update and refine the site-specific VI CSM. The following are useful resources to help with CSM development:

- NAVFAC Remediation Innovative Technology Seminar (RITS) VI presentations (NAVFAC, 2008; 2011a; 2011b; 2013; 2016; 2018). Previous RITS can be viewed here.
- NAVFAC Environmental Restoration and Base Realignment and Closure Technology Transfer (T2) VI CSM tool and checklist (NAVFAC, 2012).
- Appendix H of NAVFAC, 2015 and NAVFAC, 2016a.

Summary of Vapor Intrusion Technologies

Table 2 provides brief descriptions of the VI investigation technologies included in the matrix. The table also includes key factors, such as data quality, cost, time, and synergistic combinations with other technologies, to consider when selecting technologies, and references for more detailed information. Additional guidance documents for selecting and evaluating VI investigation technologies include:

- Recent technology-related fact sheets developed by the DoD as supplements to the DoD Vapor Intrusion Handbook (DoD, 2009). View these fact sheets at the link below: https://www.denix.osd.mil/irp/vaporintrusion/
- Additional resources include a quantitative decision framework (Navy, 2015) for weighing lines of evidence and VI guidance (e.g., DoD, 2009; U.S. Environmental Protection Agency [U.S. EPA], 2015; and Interstate Technology and Regulatory Council [ITRC], 2007, 2014).

Disclaimer

This publication is intended to be informational and does not indicate endorsement of a particular product(s) or technology by the DoD, nor should the contents be construed as reflecting the official policy or position of the DoD. Mention of specific product names, vendors or source of information, trademarks, or manufacturers is for informational purposes only and does not constitute or imply an endorsement, recommendation, or favoring by the DoD.

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Table 1. Matrix of Vapor Intrusion Investigation Technologies

			Soil Screening			Soil Vapor & Indoor Air Field Screening				Soil Vapor & Indoor Air Sampling				Forensic Tools					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
																Indicators, Surrogates & Tracers			
VI Pathway Assessment	Investigation Objective	Sub-objectives	Discrete soil samples for VOC analysis with microwave extraction	Continuous coring or profiling (MIP, Dye LIF)	Soil Physical Properties (core logging, geotech analysis)	Handheld PID (VOCs)	Portable GC/PID (Tedlar bags)	Mobile GC/ECD (Tedlar bags, glass syringes, Teflon tubing)	Portable GC/MS (HAPSITE) & MS/MS (TAGA)	Evacuated Canister with analysis by EPA Method TO-15	Active Sorbent Sampler with analysis by EPA Method TO-17	Passive Sorbent Sampler	Flux Chambers	Compound Ratio Analysis	Compound Specific Isotope Analysis	Building Pressure Differential Monitoring	Other R= Radon, TD = Temperature Differential; Tr= Introduced Tracers	Building Pressure Cycling	High Volume Soil Gas Sampling
Are VOCs/SVOCs associated with subsurface sources underneath or near the building(s) present at concentrations above screening levels?	Characterize vapor sources	Delineate vadose zone vapor sources	+++	+++ (LIF and MIP)	-	++	+++	+++	+++	+++	+++	++	-	+	++	-	-	-	+
	Characterize near source vapor concentrations	Characterize spatial distribution	+	++ (MIP)	-	++	+++	+++	+++	+++	+++	++	-	-	-	-	-	-	-
		Characterize temporal variability	-	-	-	-	+++	+++	+++	+++	+++	++	-	-	-	-	-	-	-
Are VOC/SVOC vapors migrating from the source towards the building?	Identify vapor migration pathways in the subsurface	Characterize soil migration pathways	-	+ (MIP)	+++	+	++	+++	+++	+++	+++	++	-	-	-	-	++^{Tr}	-	+
		Characterize utility conduits pathways	-	-	-	+	++	++	++	+++	+++	+++	-	+	++	-	+++^{Tr}	++	+
	Characterize near foundation vapor concentrations	Characterize spatial distribution	-	-	-	++	++	+++	+++	+++	+++	++	+	-	-	-	+	-	+++
Are buildings susceptible to soil gas entry (i.e., do openings exist for vapor entry and do driving forces exist to draw the vapors into the buildings)?	Identify building envelope vapor entry points	Characterize visually identified utility penetrations, cracks, wall cavities, sumps, etc.	-	-	-	++	+++	+++	+++	+	+	+	++	+	+	+	++$^{R, Tr}$	+++	+
	Characterize vapor entry potential	Characterize short-term and long-term driving forces for vapor entry.	-	-	-	-	-	-	-	-	-	-	-	-	-	+++	++^{R,TD}	+++	-
		Quantify foundation bulk leakage	-	-	-	-	-	-	-	-	-	-	++	-	-	++	-	+++	+++
	Characterize building ventilation	Characterize building envelope leakage and air exchange characteristics	-	-	-	-	-	-	-	-	-	-	-	-	-	+++	-	+++	-
Are VOCs/SVOCs associated with the subsurface vapor source(s) also present in the indoor environment?	Characterize indoor air exposure point concentrations	Characterize or address temporal variability	-	-	-	-	++	+++	++	+++	+++	++	-	-	-	++	++^{R,TD}	+++	-
		Characterize or address spatial variability	-	-	-	-	++	+++	+++	+++	+++	+++	-	-	-	-	++^{R,TR}	++	-

Table 1 (continued). Matrix of Vapor Intrusion Investigation Technologies

			Soil Screening			Soil Vapor & Indoor Air Field Screening				Soil Vapor & Indoor Air Sampling				Forensic Tools					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
																Indicators, Surrogates & Tracers			
VI Pathway Assessment	**Investigation Objective**	**Sub-objectives**	**Discrete soil samples for VOC analysis with microwave extraction**	**Continuous coring or profiling (MIP, Dye LIF)**	**Soil Physical Properties (core logging, geotech analysis)**	**Handheld PID (VOCs)**	**Portable GC/PID (Tedlar bags)**	**Mobile GC/ECD (Tedlar bags, glass syringes, Teflon tubing)**	**Portable GC/MS (HAPSITE) & MS/MS (TAGA)**	**Evacuated Canister with analysis by EPA Method TO-15**	**Active Sorbent Sampler with analysis by EPA Method TO-17**	**Passive Sorbent Sampler**	**Flux Chambers**	**Compound Ratio Analysis**	**Compound Specific Isotope Analysis**	**Building Pressure Differential Monitoring**	**Other R= Radon, TD = Temperature Differential; Tr= Introduced Tracers**	**Building Pressure Cycling**	**High Volume Soil Gas Sampling**
	Characterize background contributions to indoor air	Identify products containing VOCs present in subsurface	-	-	-	++	++	++	+++	+	+	-	+	+	++	+	-	++	-
		Quantify contribution of background sources (indoor/ambient) to indoor air concentrations	-	-	-	-	++	++	++	++	++	++	++	+++	+++	+	+++^{R,TR}	++	-
Relative Cost	Some technologies have different blends of fixed and variable costs, so the costs may vary in proportion to number of samples, etc.		$	$$	$	$	$$	$$$ - diminishes with number of samples	$$$ - diminishes with number of samples	$$$	$$$	$$$	$$$	$	$$	$		$$	$$
Relative Time needed to Implement	Key: 1 - fast, 2 - moderate, 3 - longer		1	2	1	1	2	2	2	3	3	3	2	1	3	1		2	2
Complimentary Technologies	See numbers at the top of each column for reference	Site-specific conditions could justify many different combinations of technologies	2,3,4	1,3,4	1,2,4	all	8,9	8,9	8,9	4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17	4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17	4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17		all	9	6, 7, 8, 9, 10, 16		6,7,8,9	4,8,14, 15 (tracers)

Ranking Description:

-	Not applicable or expected to perform poorly
+	Provides some information when combined with other higher ranked technologies
++	Useful technology for the stated objective
+++	Provides most definitive results or represents state of the art technology

Table 2. Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Soil Screening Methods			
MIP	The MIP (membrane interface probe) is a logging tool that provides information about the relative concentrations of volatile hydrocarbon and solvent contamination, along with soil electrical conductance and permeability. The probe contains a series of detectors, each of which responds to different analyte properties. MIP is useful for identifying areas of soil contamination in the vadose zone.	MIP profiles provide very detailed information on relative concentrations and are best when paired with some discrete sampling for laboratory analysis to verify absolute values of VOC concentrations. MIP can guide the selection of the number and location of probes for long-term monitoring.	
DyeLIF	The Dye-enhanced laser induced fluorescence (DyeLIF) tool combines time-resolved LIF technology with the injection of a fluorescent dye to identify DNAPL chlorinated solvents in the subsurface. As the probe is advanced through the subsurface, the injected dye contacts the soil and quickly partitions into any present DNAPL. Standard LIF tooling is then used to detect the dye-labeled chlorinated solvent DNAPLs. DyeLIF is useful for identifying the presence of NAPL phase solvents in the vadose zone as well as in the saturated zone.	Similar considerations to MIP, except that DyeLIF is specifically designed to identify DNAPLs.	
Continuous Soil Core Logging	Continuous soil core logging provides information about the geology of the vadose zone, which influences vapor migration pathways. For example, soil core logging and stratigraphic correlation can identify laterally extensive low permeability zones, which may impede vapor migration, or high permeability zones that may enhance vapor migration.	Transport through the vadose zone is an important part of the CSM for VI assessment, so cored and logged boreholes are extremely useful. This technology pairs well with soil property analyses, headspace screening, and soil vapor monitoring probe installation. It usually is relatively fast to implement and is generally affordable since drilling depths are typically 30 ft or less. The soil characterization is also useful for soil remediation design, if needed.	

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Geotechnical Analysis of Soil for J&E Model	Geotechnical analyses of soil provide quantitative measures of soil properties that control vapor migration (e.g., soil moisture content, porosity, permeability and pressure differentials). Site-specific measures of these properties are needed as input to calibrate models, such as the Johnson-Ettinger model. These properties can be determined in the laboratory (e.g., soil moisture content and porosity), or in the field with tensiometers (soil moisture) or pneumatic testing (e.g., permeability and pressure differential).	Soil texture and moisture are very important parameters that affect the effective vapor diffusion coefficient in soil. Other J&E model parameters can be included for minimal added cost. Consider collecting samples from each mappable stratigraphic unit. Site-specific measures of soil properties also are useful for soil remediation design, if needed.	
Soil Vapor and Indoor Air Field Screening Methods			
Handheld PID (PhoCheck or ppbRAE) and Fixed Gases: O_2, CO_2, CH_4 (Landtec GEM)	Handheld photoionization detector (PID) are capable of monitoring total VOCs in real time, which is useful for identifying potential indoor background sources, vapor entry ports or delineating soil vapor plumes under buildings. Typical detectors can measure VOCs from 1 ppm to over 10,000 ppm. More sensitive detectors (e.g., PhoCheck and ppbRAE) are capable of measuring VOCs down to 1 ppb.	A PID is almost always useful during VI fieldwork. PIDs need to be calibrated each day and calibration checks should be performed at least at the end of the day, and more often if the temperature is changing (e.g., outdoor work). Despite some manufacturers claims, readings lower than 0.1 ppmv may be less reliable. Portable meters capable of measuring methane, carbon dioxide and oxygen levels in soil gas (e.g., Landtec GEM) can provide very useful data to assess biodegradation of hydrocarbons, leakage across the floor during HVS testing, stability during purging prior to sampling soil gas probes. Both meters pair well with vacuum chambers and Tedlar bags.	
Portable GC/PID (e.g., Defiant Tech. FROG-4000)	Portable GC with photoionization detector (PID) units, such as Defiant Technologies FROG-4000, are battery-powered handheld analytical instruments. The PID ionizes VOCs with ionization potentials lower than the power of the lamp (e.g., 10.6 eV, 11.7 eV). Generally, PIDs are less sensitive than ECD and MS detectors, so the GC/PID is often best suited for screening purposes. For VOC analysis, vapors may be collected via dedicated glass syringes or drawn into Tedlar bag with a lung box or connected directly to the detector with tubing.	As with all mobile analyses, collect a select number of duplicate samples for analysis by a fixed laboratory to provide data to verify the accuracy. The FROG is less expensive than GC/ECD, but also less sensitive, so it is not as well suited to indoor air quality monitoring. The fact sheet "Real-Time Monitoring" (DoD, 2017) explains how this instrument can be used for continuous sample collection versus discrete sampling and provides pros and cons of survey mode versus quantitation mode.	*Real-Time Monitoring for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 002, February 2017* *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Field Deployable GC/ECD (e.g., SRI GC/ECD)	Field deployable GCs with electron capture detector (ECD) that can be shipped from site to site, but remains in a fixed location during operation. GC/ECDs are sensitive to chlorinated compounds, making lower RLs feasible. Generally, instrument run times are short (i.e., about 10 minutes) and calibrations stable, making the instrument ideal for real-time monitoring applications. For VOC analysis, vapors may be collected via dedicated glass syringes or drawn into Tedlar bag with lung boxes or connected directly to the detector with tubing.	As with all mobile analyses, collect a select number of duplicate samples for analysis by a fixed laboratory to provide data to verify the accuracy. Cost diminishes with number of analyses performed. The fact sheet "Real Time Monitoring" (DoD, 2017) explains how this instrument can be used for continuous sample collection versus discrete sampling and provides pros and cons of survey mode versus quantitation mode.	*Real-Time Monitoring for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 002, February 2017* *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017*
Portable GC/MS (e.g., Inficon HAPSITE) and Trace Atmospheric Gas Analysis (TAGA)	Portable gas chromatograph/mass spectrometer (GC/MS) units, such as the Inficon HAPSITE, are battery-powered and suitcase-sized analytical instruments that are capable of identifying and quantifying chemical vapor concentrations. The GC separates the compounds and the MS quantifies their mass. The sensitivity is enhanced by using a pre-concentrator, which is a sorbent trap through which air is drawn to trap a larger mass of the target compound(s). The instruments can also run in scan mode with higher reporting limits (RLs) for identifying potential vapor entry points or background sources.	With all mobile analyses, collect a select number of duplicate samples for analysis by a fixed laboratory to provide data to verify the accuracy. Reliability of the HAPSITE has been a challenge in some applications. Cost diminishes with number of analyses performed.	*Real-Time Monitoring for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 002, February 2017* *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017* *Use of On-Site GC/MS Analysis to Distinguish between Vapor Intrusion and Indoor Sources of VOCs, ESTCP ER-2011-19*
	The TAGA unit is a mobile laboratory owned and operated by the U.S. EPA. It includes a dual quadrupole mass spectrometer (MS) that is capable of quantifying concentrations for more than one compound continuously and in real-time at <1 part per billion by volume (ppbv). Available to DOD through EPA.	The TAGA unit is very reliable, but also costly and, owing to demand, may be difficult to schedule.	*More information about TAGA here: https://www.epa.gov/ert/environmental-response-team-trace-atmosphere-gas-analyzer-taga*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Soil Vapor & Indoor Air Sampling Methods			
Evacuated Canister Samplers (TO-15): 1 L, 6 L and Capillary Flow Controlled	An active sampling technique using flow-controlled evacuated stainless-steel canisters. Evacuated canisters can be used to sample soil gas, typically using 1 L canisters to collect grab (e.g., 5 - 15 minute) samples, or indoor and ambient air samples, typically using 6 L canisters. Indoor air samplers are generally deployed over a period of time corresponding to the receptor exposure time (e.g., 24 hours for residential settings; 8 - 12 hours for commercial/industrial settings, depending on the work day), but may be deployed for longer durations to minimize temporal variability using ultra low flow canisters which use a capillary flow controller. When designing sampling programs, consider whether the sampling results will be used to evaluate acute exposures, chronic exposures or for diagnostic purposes. Sampling numbers and duration will also vary depending on building size, contaminant types, and residential versus non-residential building use.	Need to decide whether to use batch certified or individually-certified canisters and flow controllers, 1 L or 6 L size, and whether analysis is done by TO-15 in open scan mode, selected ion monitoring (SIM) mode, or both (reporting limits are lowest and canister cleaning requirements are most intensive for SIM method). Sample durations can be anywhere from instantaneous to 2 weeks. Discounts may be available for large numbers of analyses. Canisters are bulky and may require a large vehicle for transportation. Fittings may leak if they are too loose or too tight. Some regulators require the canister to have a residual vacuum at the end of the sampling interval. Vacuum measurements before and after shipment to and from the laboratory should be made to assess possible leakage during shipping. Compared to real-time instruments, one drawback of canisters is the lag between sampling and analytical results, which limits TRIAD decisions.	*DoD Vapor Intrusion Handbook, January 2009* *Demonstration of a Long-Term Sampling Approach for Distinguishing Sources of Volatile Organic Compounds in Indoor Air, ESTCP ER-2015-04*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Active Sorbent Sampler (TO-17)	Active sorbent samplers draw vapors through sorbent tubes at constant flow rates for sufficient time to achieve desired detection limits. As the air passes through the tube, the compounds collect on the absorbent inside. The pump flow rate and sampling time are used to calculate the volume of air passing through the tube so the concentration of compounds in the air can be calculated. Although sample durations can be tailored to the needs of the program, RL requirements may preclude some shorter samples durations. As with canister sampling, sample number numbers and duration will also vary depending on building size, contaminant types, and residential versus non-residential building use.	A trip blank should be included in each shipment to verify potential blank contamination. Tubes should be shipped wrapped in foil with scavenger carbon inside their overpack container. Use Teflon ferrules to avoid damage to tubes from compression caps. Tubes should be shipped in a cooler with cold-packs or ice. Pumps require a reliable electric supply. The flow rate for active tube sampling should be 50 to 100 mL/min and the total volume of the sample should not exceed the recommended safe sample volume for the specific set of target analytes and sorbent(s). Multi-bed sorbents are available for complex mixtures of target analytes. Consider a second tube in series to verify whether any compounds were not adequately retained by the first tube during sampling.	*DoD Vapor Intrusion Handbook, January 2009*
Passive Sorbent Sampling for Soil Gas and Indoor/Outdoor Air	Passive sampling devices can provide accumulated mass or time-weighted average (TWA) concentration data for indoor air, outdoor air, soil gas, and other vapor samples (e.g., sewer vapor). Passive samplers contain a sorbent material (e.g., activated carbon) that acts as a trap for vapor-phase VOCs. There are several commercially available samplers and sorbents and selection is based on site conditions. Passive samplers are generally less obtrusive than conventional samplers and also easier and less expensive to ship. For soil gas, samplers with low uptake rates and moisture sensitivity are recommended. For indoor/air, samplers of various geometries and uptake rates are available. As with active sorbent samplers, sample durations can be tailored to the needs of the program, but RL requirements may preclude some shorter sample durations. Sample numbers and duration will also vary depending on building size, contaminant types, and residential versus non-residential building use.	A trip blank should be included in each shipment to verify potential blank contamination. Passive samplers should be shipped with scavenger carbon inside their overpack container and should be shipped in a cooler with cold-packs or ice. If a thermally-desorbable sorbent is used, the product of the passive sampler uptake rate and the duration of the sample should not exceed the recommended safe sample volume for the specific pair of target analytes and sorbent(s). Consider inter-method duplicates (e.g. TO-15 or TO-17 samples) to verify accuracy and possibly to field-calibrate passive samplers for the highest level of accuracy.	*Passive Sampling for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 001, February 2017* *Development of More Cost-Effective Methods for Long-Term Monitoring of Soil Vapor Intrusion to Indoor Air Using Quantitative Passive Diffusive-Adsorptive Sampling Techniques, ESTCP ER-2008-30.*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Flux Chambers	Flux chambers may be dynamic or passive. Dynamic flux chambers collect gaseous emissions from an isolated surface area with an enclosure device. Clean, dry sweep air is added to the chamber at a fixed, controlled rate (e.g., 0.005 m^3/min) that is selected based on site conditions. The volumetric flow rate of sweep air through the chamber is recorded and a sample of the chamber exhaust is collected. The emission rate is calculated from the surface area isolated, the sweep air flow rate, and the gaseous concentration Static flux chambers isolate a surface of interest with a steel container or plastic sheeting and a sample of the air in the chamber is collected after a fixed period of time. The mass flux is calculated as the sample concentration times the volume of the chamber divided by the sampling time period. Active chambers can be used to determine either gaseous emissions or diffusive flux. Static chambers are used primarily to measure diffusive flux.	Flux chambers are much smaller than occupied structures, and therefore spatial variability may be an issue. Consider multiple locations to assess spatial variability or large-scale flux chambers. Field personnel should be highly skilled.	*EPA USER'S GUIDE MEASUREMENT OF GASEOUS EMISSION RATES FROM LAND SURFACES USING AN EMISSION ISOLATION FLUX CHAMBER. (https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=ORD&dirEntryID=51253*
Forensic Methods			
Compound Ratio Analysis	Compound ratio analysis compares the relative proportions of compounds in paired soil gas and indoor air samples. Most recalcitrant VOCs, such as TCE and PCE, have similar mobility in the subsurface and are expected to enter an overlying building at similar rates. Therefore, the relative concentrations among these VOCs in subsurface and indoor air samples should be similar if subsurface VI is the dominant contribution of vapors to indoor air. Compounds with indoor air concentration ratios greater than soil gas concentration ratios (e.g., PCE/TCE in indoor air vs. PCE/TCE in sub-slab soil gas) are likely to indicate contribution from a background source, especially where the difference between the two ratios is larger than can be reasonably explained with normal data variability (e.g., differ by more than a factor of ten).	Consider variations on this theme, including multiple chemicals where present, visualization techniques such as pie charts, stiff diagrams, trilinear plot or multi-linear plots. Truncated data sets with high percentages of non-detect results can be challenging. Compounds with background indoor air concentrations similar to or above risk-based screening levels include benzene, TCE, PCE, chloroform, carbon tetrachloride, 1,2-dichloroethane, and sometimes others. Whenever collecting indoor air samples, an outdoor air sample (or multiple samples) is a valuable way to identify ambient outdoor air VOC concentrations, which in some cases may pose potential health risks.	*Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Indicator Tracer, and Surrogate Testing	Measuring cross-slab and cross-building pressure differentials, radon, temperature differentials, and testing with introduced tracers can be used for several purposes as part of a VI assessment, including understanding soil gas flow and vapor transport, estimating air exchange rate (AER), evaluating spatial variability in slab susceptibility to vapor entry, verifying rate of soil gas movement in response to mitigation systems, evaluating sewer gas entry into buildings, and verifying absence of leaks in sample trains.	Key considerations are building size or multiple meters to ensure getting representative measures of indoor building pressures, temperatures, and concentrations of radon and tracers (if used). The selection of appropriate parameter to test depends on study objectives and site-specific conditions.	*Use of Tracers in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No: 005, September 2017* *ASTM E741-11 Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.* *Demonstration/Validation of More Cost-Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air, ESTCP ER-2013-22*
Compound Specific Isotope Analysis (CSIA)	Natural and/or induced degradation causes the ratio of stable isotopes to change over time because microbes preferentially degrade lighter isotopes. CSIA provides characterization of isotopic ratios for VOCs of interest, which allows for the differentiation of VOCs emitted from background sources (e.g., consumer products and building materials, which typically are not subject to biodegradation) and those emitted from subsurface sources (which are often subject to significant biodegradation). Carbon (12C/13C) is most common, but chlorine (35Cl/37Cl) and hydrogen (2H/1H) have been demonstrated to distinguish between subsurface and indoor sources of VOCs. A key challenge is preconcentration without fractionation for indoor air samples, which typically have relatively low concentrations compared to subsurface samples.	Close communication with the analytical laboratory is critical. Samples may be whole-gas samples if the concentrations are high enough, but typically indoor air samples require pre-concentration, which can be performed with TO-17 style sampling using a strong sorbent or with methanol-filled impingers. Typically, at least a subsurface and an indoor air sample would be analyzed, the method is best suited to comparisons between samples.	*Use of Tracers in Vapor Intrusion Assessment , DoD Vapor Intrusion Handbook, Fact Sheet Update No: 005, September 2017* *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017* *Use of Compound-Specific Stable Isotope Analysis to Distinguish Between Vapor Intrusion and Indoor Sources of VOCs, ESTCP 2010-25*
Building Cross-Slab Pressure Differential Monitoring	Underpressurized buildings can promote subsurface vapor entry, whereas positively pressurized buildings suppress vapor entry. Measuring the differential pressure across the floor slab therefore provides valuable information to understand whether a particular building is susceptible to VI. Indoor air concentrations measured when building pressure is predominantly negative reflect the impact of VI. Indoor air concentrations measured when the building is predominantly positively pressurized reflect the impact of sources inside the building and/or outdoor air (background). Micromanometers with pressure transducers and data loggers can be attached directly to a sub-slab probe to record the cross-slab pressure differential over time.	Micromanometers are sensitive to temperature changes and should be allowed to thermally equilibrate with their surrounding before readings begin. It is helpful to use an instrument that will auto-zero itself periodically. At least 24-hours of monitoring is very useful to assess effects of HVAC operations, diurnal weather effects. Very useful with building pressure control testing and high-volume sampling to assess building ventilation rate, floor leakiness, enable radius of influence calculations and fan selection if mitigation is needed.	*Real-Time Monitoring for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No: 002, February 2017*

Table 2 (continued). Summary of Vapor Intrusion Investigation Technologies

Investigation Technology	Description	Key Considerations (quality, cost, time, synergistic combinations, etc.)	References
Building Pressure Cycling (Depressurization and Pressurization)	Building pressure cycling (BPC) is a technique that manipulates building pressure and ventilation to alternately promote or inhibit VI and minimize the influence of spatial and temporal variability on indoor air concentrations. Blower doors, existing HVAC and air handling units, and other fan types have been used in implementing this technique. The difference between indoor air concentrations measured under positive and negative pressure can indicate the contribution from subsurface sources. Under negative pressure conditions (i.e., depressurization), indoor air concentrations can provide upper bound estimates of the exposures that may arise from VI and background sources combined and, where below risk-based screening levels, provides a high degree of assurance of a condition of no significant risk. Research to date indicates results of BPC are consistent over time, so multiple events or seasonal monitoring may not be needed.	Interior walls and doors may affect air flow through the building, so the test design requires some thought and planning. For large buildings, is usually useful to engage the mechanical engineer that knows the HVAC systems in the planning stage, and possibly also the implementation stage. A real-time method of indoor air VOC concentration monitoring is a very useful addition to this method to understand temporal changes in concentrations in response to different imposed levels of depressurizations. However, indoor air concentrations have been shown to stabilize after 3 to 4 air exchanges and a single 30- to 45-minute Summa canister placed near the exiting air provides an adequate measure of the indoor air concentration for risk assessment purposes because the induced pressure differential minimizes variability. It is useful to evaluate the natural range of building conditions prior to BPC testing, to select appropriate depressurization levels for testing. Levels that are too low may not provide representative "worst case" results; levels that are too high may dilute indoor air concentrations due to excessive ventilation.	*Use of Building Pressure Cycling in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No: 004, August 2017* *Determining the Influence of Background Sources on Indoor Air Concentrations in Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 006, September 2017* *Protocol for Tier 2 Evaluation of Vapor Intrusion at Corrective Action Sites, ESTCP ER 2007-07* *Mass Flux Characterization for VI Assessment, ESTCP ER-2015-03*
High Volume Sampling	A method for assessing vapor concentrations and distributions in the subsurface, often in subslab soil gas. The approach involves removing a large volume of soil vapor from below a building slab and monitoring vapor concentrations and pneumatic response for analysis and interpretation of the vapor distribution between the point(s) of suction. In addition, the method can be used to collect data to design mitigation systems.	Exhausted gas should be either filtered through activated carbon or vented to the outside of the building through hose or pipes. This method is most effective where granular fill exists below the floor slab, and less effective if the material below the floor yields very low flow rates (fortunately not common). Consider helium interwell tracer tests, PID screening and landfill gas meter screening as complimentary technologies to provide data on VOC vapor concentrations vs distance, and leakage across the floor slab. A spreadsheet model is available for data analysis and interpretation at ESTCP ER-201322.	*High Volume Sampling for Vapor Intrusion Assessment, DoD Vapor Intrusion Handbook, Fact Sheet Update No. 003, February 2017* *McAlary et al., 2010, GWMR v30, no2, pp 73-85*