DoD Vapor Intrusion Handbook
Fact Sheet Update No: 011
Date: January 2021

Vapor Intrusion Mitigation

Purpose

The primary purpose of this fact sheet is to provide information on the selection and management of vapor intrusion (VI) mitigation technologies. This information updates Section 5 of the Department of Defense (DoD) Vapor Intrusion Handbook (Tri-Service Environmental Risk Assessment Workgroup [TSERAWG], 2009). This fact sheet includes new lines of evidence and monitoring approaches that enable more efficient VI mitigation design and operation. Optimal VI mitigation design includes understanding performance metrics and planning exit strategies to achieve closure.

The following topics are covered:

- VI Conceptual Site Model (CSM) and Building-Specific Conditions
- VI Mitigation Technologies
- Conventional Performance Monitoring
- Innovative Performance Monitoring
- Lessons Learned and Conclusions

Introduction

The Defense Environmental Restoration Program (DERP) Management Manual specifies that the need for a VI mitigation system or source remediation should be tied to a site-specific risk assessment (DoD, 2018). The DERP Manual specifies the following:

> The DoD component "*shall conduct appropriate response actions for a vapor intrusion pathway in existing structures when the potential for vapor intrusion of volatile chemicals exists and a site-specific risk assessment indicates an unacceptable risk to human health due to a release to the environment that is the responsibility of the DoD*…" (DoD, 2018).

Multiple lines of evidence, including subsurface sampling and mathematical modeling, may be used to evaluate the VI pathway. If the results of subsurface sampling and/or mathematical modeling indicate a potential for unacceptable risk, the DoD Component should conduct a site-specific risk assessment based on ambient (outdoor) and indoor air sampling to determine whether a significant site-specific risk exists. Indoor air contaminants must be identified and differentiated from "background" indoor air emissions unrelated to VI. These background emissions can occur from sources such as consumer or household products (e.g., cleaners, gasoline, solvents), internal structure activities (e.g., dry cleaning), or operational activities of other parties. *Note: potential imminent safety risks associated with fire and explosion for high levels of methane or petroleum hydrocarbons (PHCs) should be referred to the Base Fire Marshal and are not addressed in this fact sheet*.

If VI mitigation is justified based on a site-specific risk assessment, the selection of an optimized approach depends on building-specific conditions. Because VI processes depend strongly on various building characteristics and site-specific conditions, generic approaches for VI mitigation may not be optimal. This fact sheet provides information to aid in identifying the optimal technology or combinations of technologies and performance metrics for building-specific conditions. Recent advances in VI mitigation technology design and performance monitoring are discussed. This fact sheet also supports the development of an exit strategy for VI mitigation to avoid unnecessary effort and cost in operations.

VI CSM and Building-Specific Conditions

The CSM plays an important role in determining the optimal approach to VI mitigation. Figure 1 provides a simplified approach for technology selection that is based on volatile organic compound (VOC) mass loadings (mass flux multiplied by building area [A]) along the VI pathway. This basic approach assumes the VI process occurs as follows:

1) An upward mass loading of chemicals through the vadose zone (ML_{SOIL}), typically dominated by vapor diffusion from a source of concentration C_o at some depth (L) below or very near a building, where D_{eff} is the effective vapor diffusion coefficient;
2) A mass loading across the foundation (ML_{FND}) resulting in mass loading (mass flux times area) to the building that is usually dominated by advection at a concentration of C_{ss} and a flow rate of Q_{SOIL} in response to a pressure differential (ΔP) across the foundation; and
3) The mixing and dilution of the mass loading of vapors entering the building (ML_{BLDG}), which is governed by the ventilation rate of the building (Q_{BLDG} = volume x air exchange rate) to result in an indoor air concentration (C_{ia}).

All three loadings are theoretically equal under ambient conditions over long-term average conditions where the building foundation is transmissive to vapor transport, although there are temporal variations in the short term. As listed in Figure 1, one or more of these key processes can be altered to minimize or prevent VI using a variety of technologies.

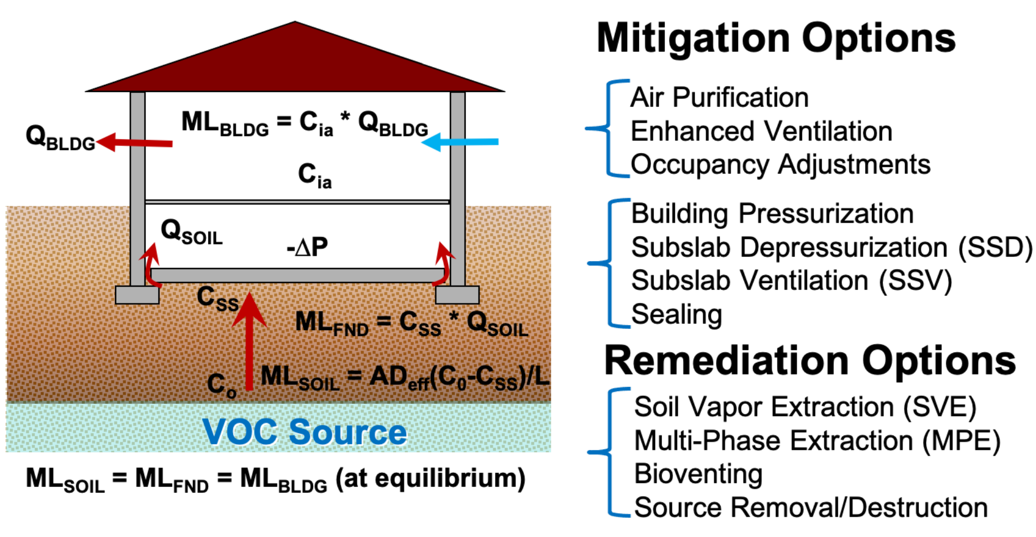

Figure 1: Conceptualization of VOC Mass Loadings with Corresponding Options for Mitigation and Remediation

The optimal risk management program may contain different combinations of these technologies over time. Other site-specific considerations include the nature and extent of contamination, the fate and transport of chemicals, building conditions (build-quality, ventilation, occupancy, etc.), stakeholder concerns, practicality, cost and other factors such as a margin of safety to account for uncertainties.

Building-specific conditions will often impose constraints on the selection of mitigation technologies. Examples include: 1) subslab venting may be difficult or require dewatering if the floor slab is at or near the water table; 2) indoor air filtration may be impractical if the building volume is too large; and 3) floor sealing may be impractical if there are too many obstructions. For a new building, a passive venting system may be implemented with a contingency to upgrade to an active venting system if monitoring results show the passive system is not adequately protective. Preferences of building occupants, owners, and regulators may also influence the technology selection. Furthermore, operation and monitoring data may inform ways a system can be optimized over time (e.g., adjusting the applied vacuum of a SSD system to focus on the vent pipes yielding the highest rate of mass removal). For large buildings, it may not be necessary to mitigate the entire footprint and the area needing mitigation may shrink over time. Table 1 summarizes the building-specific conditions that influence the VI mitigation selection and design approach.

Table 1: Building-Specific Conditions that Influence the VI Mitigation Selection and Design Approach

Factor	Description
Source Characteristics	The source location relative to the building is a key factor, along with source depth, mass, VOC concentrations, emission rate, and chemical composition. However, a focus on concentrations only can be misleading. For example, a lower concentration in a dry, sandy soil may result in higher emissions than a higher concentration in moist, clayey soils. Vadose zone sources pose a higher potential risk than groundwater sources but can be more easily remediated over time. A source directly beneath a building generally poses a higher potential risk than a downgradient source beside a building. In addition, the dominant compound in a contaminant mixture may not be the risk-driver if a less concentrated compound has a higher toxicity.
Slab and Subslab Configuration	It is important to document the relative gas permeability of the floor slab and materials below the building floor. The transmissivity of the material below the floor and the leakance across the floor slab can be determined using routine pneumatic test data (see the spreadsheet model in Environmental Security Technology Certification Program [ESTCP] ER201322). Where the slab is well-constructed, well-sealed, and unfractured and the material below the slab is highly permeable, SSV can be implemented cost effectively. The radon mitigation industry tends to focus on SSD as vacuum measurements are fast and affordable. However, where the material below the slab is highly permeable, the high flow rates needed to achieve typical target vacuum levels (~4 to 10 pascals) may be more than necessary to reduce subslab concentrations to levels that pose no significant risk. In such cases, SSV is a more energy-efficient option than SSD.
Building Pressure and Ventilation	Building pressure is a critical factor because negative pressure promotes VI. Many factors can affect the pressure inside the building including mechanical fans, wind, and barometric pressure changes. Most large buildings have heating, ventilating, and air conditioning (HVAC) systems with exhaust fans, make-up air, and recirculation systems. These HVAC systems are designed to meet building codes for fresh air supply, air exchange rates, and occupant comfort. While the HVAC systems are typically balanced to maintain a near-neutral pressure, this is not always achieved. Building pressure and cross-slab differential pressure can be monitored with datalogging digital micromanometers. The results depend on air tightness of the building, leakiness of the slab, inflow/outflow rates, HVAC duty cycles, the occupants' activities, weather conditions, and more. The design and performance monitoring for mitigation systems should be customized to these conditions to some degree.

Table 1 (Continued): Building-Specific Conditions that Influence the VI Mitigation Selection and Design Approach

Factor	Description
Building Design and Build Quality	Building design and build quality are other important variables. Mitigation design and operation must consider the following factors: whether a building is new or old; large versus small; in a warm or cold climate; tall versus short; occupied versus unoccupied; military grade versus standard specification; energy-efficient versus drafty; has a crawlspace or basement or slab-on-grade foundation; and the future land use in the case of vacant land.
Future Land Use	If a building or property is changing use, the mitigation design may need to anticipate future building and receptor conditions. In areas where there is currently no building, future buildings may warrant mitigation systems, which can be more efficient if construction methods are chosen to facilitate mitigation (U.S. Environmental Protection Agency [EPA], 1994b). The DERP Manual (DoD, 2018) indicates modeling can be used to assess potential future risks and to support notifying landowners or facility operators to perform a building-specific risk assessment or install mitigation systems in new construction, as appropriate.

In summary, it is important to design and operate a VI mitigation system that is well-suited to the building-specific conditions and cost-effectively achieves system objectives. This is seldom a one-size-fits-all proposition and customized designs will better ensure cost-effective systems are implemented.

VI Mitigation Technologies

The focus of this fact sheet is on building-specific mitigation to interrupt or reduce the impact of a complete VI pathway. As summarized in Table 1, the technologies described include SSD, SSV, building floor aeration or building interior ventilation, barrier technologies, and soil vapor extraction (SVE) adjacent to or under buildings. Various remedial technologies, such as in situ chemical or biological treatment, are available to mitigate VI by reducing the source of the VOCs in the subsurface. Additional resources on in situ remedial options for VOCs can be found at the Federal Remediation Technologies Roundtable web site at https://frtr.gov/matrix.

Understanding the capabilities and limitations of each mitigation or source remediation technology is an important step in selecting the technologies and the sequence of application. Key considerations are listed in Table 2 regarding the benefits and limitations of these technologies. For existing buildings, SSD and SSV are the most common mitigation technologies (U.S. EPA, 2008). Innovative technologies of note for VI mitigation include incorporating the use of aerated floors and barriers, which are described below.

Table 2: VI Mitigation Technology Benefits and Limitations

Technology	Description	Benefits	Limitations
Subslab Depressurization (SSD), also known as Active Soil Depressurization (ASD)	Extracts gas from below the floor to cause a vacuum and curtail advection of soil gas into the building.	Conventional monitoring includes static vacuum measurements. Vacuum is easy and inexpensive to measure.	Does not prevent diffusion of vapors through concrete where subslab concentrations are high. May not work in a wet basement or with a shallow water table. Costly compared to SSV if subslab permeability is high as target vacuum levels may be excessive.
Subslab Ventilation (SSV)	Reduces vapor concentrations below the floor such that	Cost effective where material below the slab is highly permeable and/or	Diagnostics and performance monitoring require a higher level of effort than SSD. May

Table 2 (Continued): VI Mitigation Technology Benefits and Limitations

Technology	Description	Benefits	Limitations
	any potential vapor transport across the foundation carries no significant mass of VOCs into the building, regardless of pressure gradient. May need air inlets to enhance air flow rates.	initial concentrations are low. Suitable for use with aerated floors in new construction. Effective for aerobically-degradable compounds such as PHCs and methane. Passive ventilation can be used if the permeability is high enough.	require tracer testing and/or frequent sampling and analysis to assess mass removal rates. Not suitable for existing buildings with moderate to low permeability materials and high VOC concentrations (e.g., >1E^{6} µg/m^{3}) below the floor.
Crawlspace Ventilation	Reduces vapor concentrations in the crawlspace by dilution.	Practical where a vapor barrier is present below the floor to minimize downward flow of conditioned indoor air.	May lead to problems in cold climates if water pipes are present in the crawlspace. May lead to excessive loss of conditioned indoor air.
Submembrane Depressurization	Similar to SSD but applied in buildings with crawlspaces where a membrane is placed at ground surface.	Suitable for crawlspaces because it captures vapors below the membrane with minimal flow rates. Maintains temperature and humidity in the crawlspace at acceptable levels.	May be difficult to install if the crawlspace height is minimal. Potential for damage to the membrane if there is foot traffic in the crawlspace.
Barriers	Includes both liners below a floor slab and epoxy-like coatings on top of the slab. Often intended as a standalone solution with minimal long-term stewardship requirements. May also be used in conjunction with other technologies.	Reduces advective and diffusive transport of VOCs across the floor. May be effective as a standalone mitigation solution. Improves the radius of influence of active SSD/SSV systems by minimizing leakage across the slab. May be sufficient with passive venting when the flux of vapors is low. Relatively easy to install during new construction.	Quality assurance during construction is very important to ensure integrity and longevity. Diffusion through barriers can still be problematic if subslab concentrations are high. In the absence of any venting below the barrier, concentrations may build up to unknown levels. Monitoring must not compromise the barrier. Installation in existing buildings is potentially challenging.
Aerated Floors	A layer with very high gas permeability embedded in a floor.	The initial capital cost can be offset by reduced operation and maintenance (O&M) costs because fewer and smaller fans are needed. Passive venting may be sufficient.	Best suited to new construction because existing buildings may have immovable features that are challenging to install an aerated floor around.
Indoor Air Pressurization	Increases air flow into the building to create a pressure that suppresses VI.	Achieved rapidly for buildings with HVAC units that can move sufficient air, so especially useful as a first response. Pressure is easy and inexpensive to measure.	Not practical in leaky buildings. Requires close coordination with building and HVAC personnel. In areas of hot or cold climates, the cost of heating or cooling may be prohibitive. Long-term stewardship requires

Table 2 (Continued): VI Mitigation Technology Benefits and Limitations

Technology	Description	Benefits	Limitations
			dedication to maintaining filters, fans, and HVAC settings.
Indoor Air Filtration	Uses air purifying filters to remove VOCs from indoor air.	Reduces VOC concentrations to some degree via adsorption or destruction. Deployed rapidly. Well-suited for small spaces such as individual offices, small homes, or apartments.	Filter replacement cycle typically is controlled by non-target compounds and may be difficult to predict or costly to monitor. Large indoor spaces may have a ventilation rate too high to treat cost-effectively. Exposure may occur before filtration in some cases. Occupants may interfere with operations of portable air filters.
Indoor Air Ventilation	Increases the air exchange rate to reduce concentrations of VOCs by dilution.	Reduces concentrations of VOCs in indoor air via dilution and mixing. Most common solution for industrial hygiene air quality concerns. Easily and rapidly implemented in temperate climates. Well suited for an interim response action.	Occupant comfort is a concern in hot or cold climates. Interior walls or partitions may limit the effectiveness of ventilation from exterior doors or windows. Monitoring effort is likely to be high because several external factors (e.g., wind, weather, etc.) affect building ventilation rates.
Soil Vapor Extraction (SVE), Multiphase Extraction (MPE), and Other Source Remediation Technologies	Removes as much mass as practical from below or near the building. Remediates conditions unacceptable for unlimited use and unrestricted exposure.	Reduces or eliminates the VOC source beneath a building. SVE has a large radius of influence and is best suited to sites with VOCs in the unsaturated zone. SVE generates a vacuum below the floor of the building to curtail advection of soil gas into the building.	Capital and O&M costs tend to be higher than mitigation technologies, and there is a return on this investment only if the increased effort reduces the duration of operations or has collateral benefits such as source remediation in the soil.

Aerated Floors

For new construction and comprehensive renovation of existing buildings, the floor can be designed with an engineered system of very high permeability beneath the floor slab (referred to as aerated floors). Many commercially-available technologies exist for creating a high permeability layer. If air entry to the aerated layer is restricted, it is usually easy to generate a uniform vacuum in the aerated layer with minimal power. If air entry is promoted, it is usually easy to maintain a high rate of subslab ventilation with minimal power. An aerated floor may be passively ventilated, combined with a wind-driven turbine or other low cost/low maintenance method of venting such as solar powered fans, or a powered fan can also be used if needed.

Barriers

Advances in barriers (both above and below the floor slab) have gained increasing traction in recent years, especially for new construction and redevelopment. Plastic sheets have been used as water vapor barriers below floor slab for decades, but polymers such as ethyl-vinyl alcohol (EVOH) provide a higher level of resistance to permeation by VOCs (Jones and Rowe, 2016). Thickness is a key consideration. Some guidance documents recommend very thick membranes for durability (e.g., 60 mil [U.S. EPA, 2008]) but the rigidity of such thick plastic sheets makes them more difficult to place. A spray-applied liner may be more practical or a thinner membrane (e.g., 20 mil) may be sufficient, particularly when the liner is only one component of the system. Coatings for the top surface of the concrete slab are most practical when the slab is completely accessible with minimal differential settlement. These coatings require a multi-stage application (etching, primer, epoxy, possibly more than one coat) for durability, which can be labor-intensive and require periodic inspection to verify continued adhesion to the slab. Barriers offer a potential benefit of minimal long-term costs, particularly where the potential for VI is minimal and they are implemented as a single standalone technology, provided that long-term indoor air or other monitoring requirements do not offset O&M costs.

Conventional Performance Monitoring

Diagnostic testing and periodic monitoring ensure the proper design and long-term stewardship of SSD/SSV systems, which are the most common of the conventional VI mitigation technologies.

Conventional SSD Diagnostic Testing

Diagnostic testing is usually performed to some degree for SSD systems to:

- Provide design parameters (e.g., radius of influence of a suction point);
- Verify the design components (e.g., fan size, number of suction points);
- Balance components (e.g., adjust valves to either apply vacuum evenly or direct vacuum to areas of greatest mass removal rates);
- Support regulatory approval; and/or
- Meet contractual requirements.

Static vacuum measurements are typically a key component and they are usually implemented following guidance such as that provided by U.S. EPA (1993). However, this document acknowledged that “SSD systems tend to perform effectively with fewer pipes than would be predicted based upon the effective suction radius derived from these diagnostics.” Static vacuum measurements are also affected by drift (seasonal stack effects) and noise (wind-gusts, etc.), so vacuum alone is not an ideal performance metric (McAlary et al., 2020, ESTCP ER-201322).

Indoor air sampling and analysis can be used to demonstrate that concentrations are lower than target concentrations for the target compounds. However, temporal variability and background sources can often complicate the interpretation of these data. Several common VOCs (benzene, trichloroethene [TCE], tetrachloroethene, 1,2-dichloroethane, chloroform, carbon tetrachloride and ethylbenzene) are detected frequently in indoor air not associated with VI (U.S. EPA, 2011). The generic default screening levels in regulatory guidance for these compounds in indoor air are similar to typical background concentrations, so there is a high risk of an inaccurate conclusion that the mitigation system is not effective unless a forensic analysis is performed to quantify background contributions. This concern may not be problematic if building-specific target concentrations are developed that are different than regulatory screening levels. Indoor air concentrations also vary from day to day because of weather dynamics and other factors, so typical samples of 24-hour or less duration often yield concentrations that may be different than long-term average values by 10 times or more (Holton et al., 2013; U.S. EPA, 2012). For comparison to chronic risk screening levels, it may be preferable to monitor using longer-duration samples (e.g., 7- to 30-day samples, see ESTCP ER200830 and ER201504). Note that a 90-day sample is referred to as a "short-term" sample in the radon industry.

Periodic Monitoring of SSD/SSV Systems

Periodic monitoring throughout the lifecycle of operation is a component of good long-term stewardship of mitigation systems. At a minimum, there is usually at least a U-tube manometer on suction pipes of active mitigation systems for visual confirmation that the applied vacuum meets the design level, although automated electronic alarms with audible or telemetry-based signals are increasingly common. Other monitoring activities include:

- Static vacuum monitoring at communication test points (for SSD systems)
- Flow velocity measurements in vent pipes (for SSV and SSD systems)
- Visual inspections of epoxy floor coatings and joint caulking (for barriers)
- Power draw monitoring (for active systems with electrical fans)
- Indoor air sampling and analysis (for all types of systems)
- Effluent concentrations and stack discharge monitoring (where required by air discharge permits).

The frequency of performance monitoring is sometimes specified in guidance documents, but tends to include winter as a season expected to potentially promote VI via the "stack effect" (e.g., warm air inside the building creates convection that results in a pressure gradient inside the building with the lowest pressure being at the lowest level). The duration of monitoring is usually either considered perpetual or until the source of vapors no longer poses a potential VI concern. Commercially available fans for radon mitigation are also commonly used for VOC mitigation and generally have a long service life (e.g., a decade or so). When the lifecycle of a system is expected to be longer than a decade, plans should be made for fan replacement. Placards are normally included to provide contact information in the event of alarm conditions or damage to the system components.

Roles and responsibilities for operation, maintenance, and monitoring (OM&M) should be clearly defined and OM&M plans should include succession planning because the duration of operation may be longer than the tenure of individuals in their specified roles.

Optimization should be conducted throughout the project lifecycle. During the operation of a system, the remaining mass of VOCs in the source may diminish significantly, so it may be practical to scale the system down over time (fewer suction points or smaller fans) or focus the system (restrict flow from suction points with minimal mass removal rates to focus vacuum and flow to suction points with the highest mass removal rates).

Regulatory guidance and standards for VI mitigation also do not typically include requirements to collect data to support a closure strategy, other than turning the system off for some period of time and performing a VI assessment as if no system had yet been installed. In many VI mitigation systems, the primary performance metric is subslab vacuum and adding monitoring of mass removal rates can support closure.

Effective OM&M includes periodic assessment of the floor slab integrity, building modifications, occupancy, HVAC operations, and VI mitigation system components. If property transactions occur, a process should be implemented to notify new owners of the system components, OM&M procedures, and regulatory reporting requirements. The consequences of neglecting any or all of these items should be documented using environmental covenants, deed notices, or other institutional controls. Prior to property transfer, Remedial Project Managers (RPMs) should coordinate with environmental counsel and real estate counsel as appropriate.

The rate of mass discharge from mitigation system stacks is often low enough that off-gas treatment is not required, but there are jurisdictions and cases where treatment is needed to meet the substantive requirements of air-discharge regulations. Where the stack discharge has concentrations above indoor air screening levels, it is important to assess the potential for re-entrainment of the effluent vapors to indoor air, particularly where there are roof-mounted air handling units (AHUs) that supply air to the building. AHUs often have flow rates of thousands or tens of thousands of standard cubic feet per minute (scfm) and can completely capture all of the discharge from a SSD/SSV system with a flow rate of hundreds or thousands of scfm when there is no wind or the AHU is downwind of the discharge stack, which would completely negate the effect of the system. Radon mitigation guidance typically specifies items like stack height and separation distance between the stack and opening to the building, but the degree of dilution required to meet target levels for indoor air radon concentrations may be very different than for VOCs. The indoor air mitigation level for radon in the U.S. is 4 pCi/L, which corresponds to a lifetime incremental cancer risk (LICR) of about $1E^{-3}$. VOC indoor air screening levels are often set at a LICR level of $1E^{-6}$, so much more dilution may be needed.

Innovative Performance Monitoring

While SSD/SSV are conventional technologies, new approaches for evaluating their VI mitigation performance include pneumatic testing, tracer testing, and stack discharge monitoring. Recent advancements also include the identification of preferential pathways and the use of digital monitoring/telemetry. These new monitoring approaches can provide a more comprehensive understanding of SSD/SSV performance and include an evaluation of the following:

- Radial profiles of static vacuum, subslab gas velocity, travel times, and the proportion of flow across the floor;
- Stack discharge monitoring for comparison to mass loadings from building depressurization tests; and
- A flux-balance approach for assessing the radius of influence.

An overview of these innovative performance monitoring techniques is provided below. More information can be found in McAlary et al. (2020).

Pneumatic Testing

The interpretation of pneumatic testing results is based on a mathematical model known as the two-layer model (Hantush and Jakob, 1955), which has been applied to SVE systems for decades (Thrupp et al., 1996, 1998; Beckett and Huntley, 1994; U.S. EPA, 2001). The two key parameters in this model are the transmissivity (T) of the material below the floor slab and the leakance (B) of the slab, which can be uniquely determined by fitting the model equations to two sets of data: 1) vacuum versus time (Figure 2a) and 2) vacuum versus distance (Figure 2b).

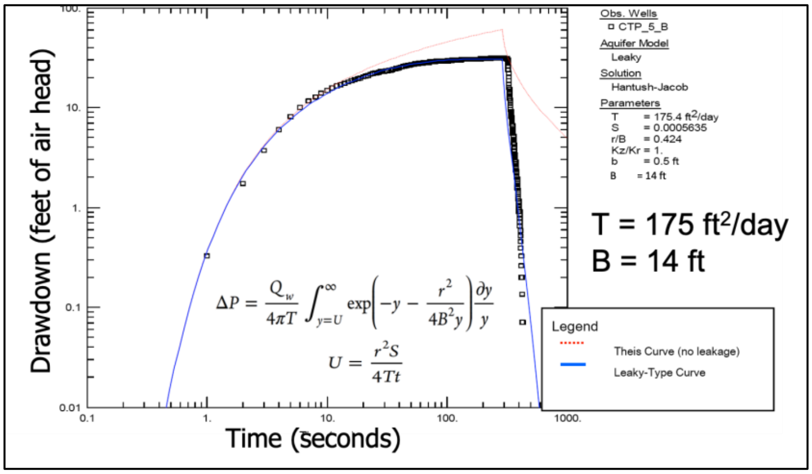

Figure 2a: Vacuum versus Time Data and Transient Model Analysis using AQTESOLV® Software

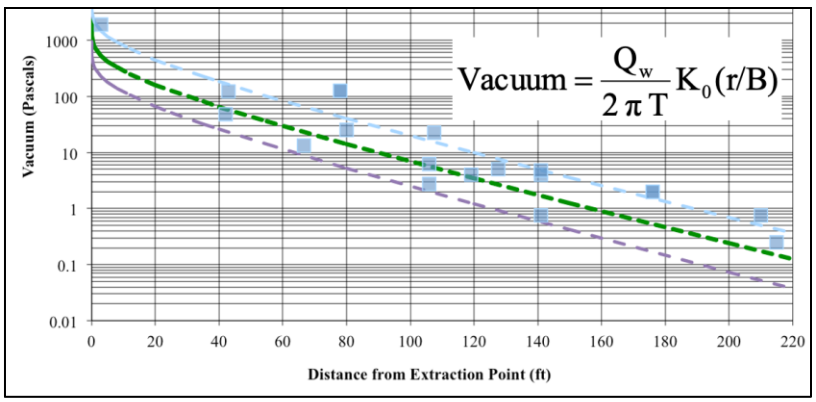

Figure 2b: Vacuum versus Distance Data and Steady-State Model Analysis Using a Spreadsheet

The vacuum versus time data typically fits the model very well (Figure 2a) because the T and B values are not changing during the test. The vacuum versus distance data typically show some variability (Figure 2b) because the slab is not uniformly leaky, so B is not constant at all locations. Locations that show lower vacuum than expected from the best fit curves on Figure 2b indicate that there is a supply of air that helps to dissipate the vacuum, which is one of the few available methods to identify the presence and indicate the general location of preferential pathways beneath or across the slab. The fitted T and B values can be used to assess the radius of influence using multiple lines of evidence (McAlary et al., 2020) and a statistical analysis of hundreds of such analyses indicates that conventional design diagnostics would likely result in more than twice as many suction points as needed.

Tracer Testing

Subslab helium tracer testing has also been recently demonstrated and validated (ESTCP ER201322) as a method to verify the velocities and gas flow beneath a floor slab in response to SSD/SSV operations.

Two methods are available:

- Inter-Well Test: Inject a small volume of 100% helium in a probe some distance from the suction point and monitor the concentration in the vent pipe to document the arrival.
- Flood Test: Reverse the fan and blow air into the subsurface, adding about 1% helium, then monitor probes at various distances to document the arrival.

Figures 3a and 3b show data from inter-well and flood tests, respectively. For a given flow rate of extraction from a suction point, the velocity versus distance profile will be faster if the region of active flow beneath the slab is thin and slower if thick, so this can provide useful insight into the vertical reach of the venting system. Testing to date has shown a range of results from 75 ft of travel within 2 minutes to less than 5 ft of travel in 5 minutes, which are dramatically different, even when the profiles of vacuum versus distance were not dramatically different. The tracer test methods also help to assess whether structural walls have footers that isolate subslab flow between portions of a building. These tests can be used to document the subslab ventilation rate for cases where SSV can be effective when the permeability below the slab is very high and excessive gas extraction is needed to generate conventional vacuum distribution below the floor.

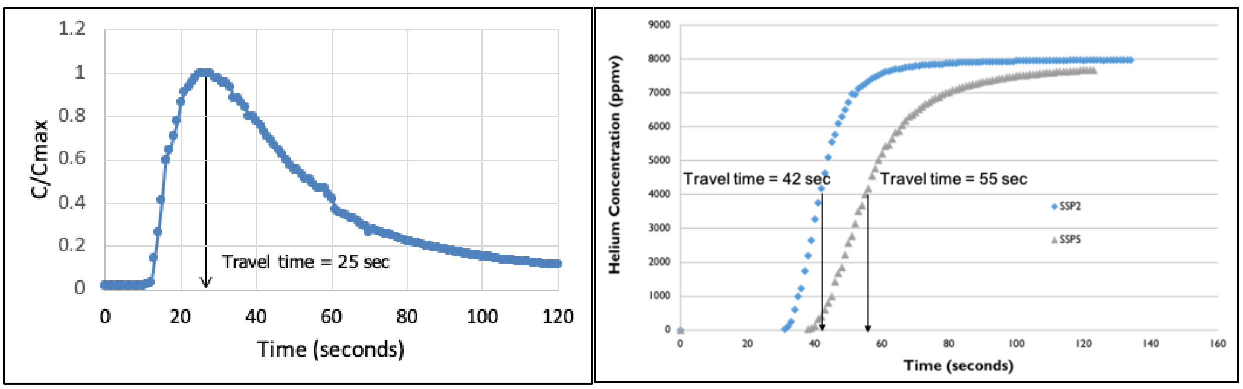

Figure 3: Tracer Test Plots for Inter-Well Test (3a, left) and Flood Test (3b, right)

Stack Discharge Monitoring

Mass discharge rates (or loadings) from the stack of a mitigation or remediation system are another method of performance assessment that has been recently demonstrated and validated (ESTCP ER201322, ESTCP ER-201501, and ESTCP ER201503). The flow rate of a suction pipe multiplied by the concentrations of VOCs in the extracted gas gives the rate of mass removal per unit time (also known as mass discharge rate, mass loading). For a system of multiple suction points, this is a very useful way to assess which points provide the most benefit in terms of containing VOCs that might otherwise enter the building. In cases where field screening is implemented, a photoionization detector (PID) can often be used as a primary instrument for subsequent monitoring, with periodic verification by laboratory sampling and analysis. Flow velocity is measured with a thermal anemometer, vane anemometer, or critical orifice flowmeter. The volumetric flow rate is obtained by multiplying the velocity by the cross-sectional area of the inside of the pipe.

The mass discharge rate can be divided by the typical building ventilation rate (building volume multiplied by the air exchange rate) to provide a conservative estimate of the long-term average indoor air concentration that might occur if the system was not operating (Cia_{LTA}). If Cia_{LTA} is higher than chronic risk-based screening levels, continued mitigation is justified. If Cia_{LTA} is lower than screening levels, this indicates there might not be enough VOC mass available to pose a potential risk to building occupants, and this provides a line of evidence toward terminating the mitigation program.

A baseline for comparison of the mass discharge from the VI mitigation system can be obtained by building pressure cycling (ESTCP ER201503). The building can be depressurized by extracting air from the building using fans, which will promote VI. The VOC concentrations in indoor air are measured after allowing the volume of the building to be purged a sufficient number of times to approach steady conditions under negative pressure. The concentrations can be multiplied by the air flow rate used to depressurize the building at the time of sample collection to provide a measure of the building mass loading rate. If the mitigation system removes VOCs at a rate equal to or higher than the building mass loading rate, the system is likely to be protective and this can function as a performance metric.

Preferential Pathway Identification and Assessment

Preferential pathways can be challenging to identify and locate. SSD performance diagnostics can also identify potential preferential pathways. If gas is extracted from beneath the floor and the vacuum is measured below the floor at multiple locations, there should be a fairly consistent trend of vacuum versus radial distance from the suction point (e.g., 6 of the 7 points shown on Figure 4). In the proximity of a preferential pathway, the vacuum will be lower than the expected value from the trend among other probes because the supply of air from the preferential pathway partially dissipates the applied vacuum (e.g., the point at a radius of 15 ft in Figure 4). This can indicate the presence and general location of a preferential pathway. Patterns in mass discharge rates can also be used to identify preferential pathways (see the Layton Utah case study in ESTCP ER201322 and ER201501). Refer to the TSERAWG fact sheet on preferential pathways for more information (TSERAWG, 2020).

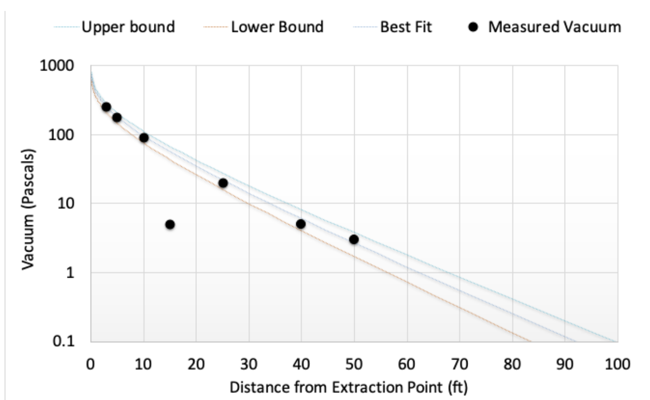

Figure 4: Example of Lower-than-Expected Vacuum at a Probe Near a Preferential Pathway

Digital Monitoring and Telemetry

Advances in electronics and telecommunications provide new capabilities for monitoring and optimizing the operation of mitigation systems. Digital micromanometers can be used to monitor the cross-slab pressure differential in real time and guide adjustments to a variable-speed controller on the fan(s) used for SSD. This can be used to maintain and document target levels of applied vacuum without excessive electrical power draw. This can also help to avoid wasting energy associated with conditioning indoor air that is subsequently drawn into the subslab region and then vented above the roofline (Moorman, 2009).

Lessons Learned

Mitigation system design and operation can face several common challenges. Lessons learned from resolving these challenges are presented in Table 3. Table 3 is not intended to be comprehensive but provides an indication of the range of building-specific challenges that may be present at DoD facilities.

Table 3: Lessons Learned for VI Mitigation Challenges and Potential Resolution

Challenge	Potential Resolution
Large source mass and high concentrations below the floor slab	Add SVE, MPE, or other mass removal/destruction technologies.
Large buildings where subslab concentrations span a wide range (e.g., TCE vapor concentrations from <100 $\mu g/m^3$ to >100,000,000 $\mu g/m^3$)	Delineate areas where mitigation is warranted/not warranted. Consider developing building-specific subslab screening levels using building-specific attenuation factors to distinguish between zones.
Large buildings with multiple air zones with different pressure and ventilation	Interface closely with HVAC personnel to understand the duty-cycle of the AHUs, review recent test and balance reports, and measure cross-slab and cross-building differential pressure over time to assess pressure dynamics. Tune mitigation system.
Large buildings where the mitigation area is far from an external wall and rooftop load capacity is limited	Consider long pipe runs across the rooftop from roof penetrations above suction points to sidewalls of the building where blower and off-gas treatment system access is available. Take care to avoid damage to membranes on flat roofs.
Wet basements (shallow water table close to or coincident with bottom of floor slab, making conventions SSD/SSV impractical)	Sumps are often fed from a perimeter drain that contains coarse granular fill and the headspace of the fill often has a high gas conductivity, so sump depressurization may be effective. Otherwise consider floor coatings, low-profile aerated floor overlay systems, increasing ventilation rate, indoor air filtration, and changes in occupancy.
Low-permeability materials below the floor slab (i.e., gas extraction rates less than 10 scfm at applied vacuum > 10 inches of water column from a conventional suction pit)	If the slab has good integrity, it can be feasible to achieve good vacuum propagation with minimal flow, but this may not prevent diffusive transport across the slab if vapor concentrations are high (i.e., $>1E^5$ $\mu g/m^3$) because the low gas extraction rates are not able to effectively reduce subslab concentrations. Consider adding indoor air quality monitoring to verify protectiveness and purification or ventilation as needed.
Complex foundations (slab conditions and subslab materials), old buildings or large buildings constructed in stages with variations in foundation design and materials	Perform a detailed review of as-built drawings and building specifications. Identify zones of differing conditions and conduct assessment and diagnostics for each zone as needed.
Preferential pathways into the building (utility chases, sewer pipes, granular fill around utilities, etc.) and across the floor slab (unsealed expansion joints, stress fractures, floor drains, utility penetrations, etc.)	Perform visual inspections, review utility drawings, consider smoke tests, thermal imaging, tracer testing, pneumatic testing and building pressure cycling to assess presence and locations of preferential pathways. Consider sealing as appropriate. Traditional SSD/SSV systems may not capture vapors originating from sewers or drains, so consider mass discharge monitoring at multiple flow rates and potentially compare to building loadings during building pressure cycling tests.
Poor foundation design or condition (field-stone walls, disintegrating	Consider sealing, new slabs, building demolition, spray-on sealants, sub-membrane depressurization, changes in occupancy,

Table 3 (Continued): Lessons Learned for VI Mitigation Challenges and Potential Resolution

Challenge	Potential Resolution
concrete, settlement, dirt floors, soakaway drains, uncovered sumps, etc.)	changes in building ventilation and/or SVE where the vadose zone is suitably permeable and thick.
Diffusive transport (where subslab vapor concentrations are very high, i.e., >1E^5 μg/m^3)	Consider adding indoor air purification or ventilation prior to and during the initial period of operation of a mitigation system because vapors diffusing through concrete may continue to pose indoor air quality concerns until subslab concentrations are reduced, which may take some time. Consider SVE and/or MPE for aggressive mass removal.
Highly-powered HVAC conditions such as clean-rooms, fume hoods, kitchen fans, paint-booth ventilation, etc. that depressurize rooms or buildings and exacerbate VI	Interface closely with the HVAC personnel to understand dynamics of inflows, outflows, and pressure differentials. Use digital micromanometers and dataloggers to monitor cross-slab and cross-building differential pressures over time, observe room-to-room air flows using smoke pens, be aware that block walls may have cavities that can act as preferential pathways, and focus field screening and sampling locations to assess areas of low pressure in appropriate detail. Consider an audit to assess whether HVAC meets current building codes and update as appropriate.
Potentially explosive levels of methane or petroleum hydrocarbon vapors	Notify Base Fire and Emergency professionals. Employ intrinsically safe and/or explosion-proof equipment as appropriate. Methane mitigation may be subject to additional regulations, guidance, or standards.
Odorous compounds such as hydrogen sulfide or mercaptans	Consider downwind dispersion from any vent pipes and the potential for odor complaints. Assess options for scrubbers or enhanced dispersion (e.g., taller stacks).

Conclusions

The following factors are key elements to successful VI mitigation projects:

- Select the technologies to suit the building-specific conditions.
- Design the system to be protective with a margin of safety for uncertainty while avoiding excessive over design.
- Select performance metrics to demonstrate effectiveness and support a future exit strategy.
- Plan from the outset for long-term stewardship.
- Be prepared to modify mitigation systems as needed if conditions change over time (i.e., if the mass removal rate gradually decreases to levels too low to pose a potential risk, be prepared to reduce the fan power and/or number of suction points).
- Communicate effectively with stakeholders (building occupants, owners, regulators, etc.) regarding the logic for needing a VI mitigation system, the basis for the design, the installation process and timeline, the monitoring program and schedule, reporting and notifications for any unexpected repair that may be needed.

Additional Resources

For the past few decades, the most commonly cited standards for VOC VI mitigation were developed by radon researchers (e.g., U.S. EPA, 1986, 1991, 1993, 1994a, 1994b, 1994c; ASTM, 2013 and 2008; American Association of Radon Scientists and Technologists (AARST), 2012, 2017, 2018a, 2018b, 2018c), presuming the processes affecting VOC vapors and radon are sufficiently similar. The U.S. EPA has published an Engineering Issues Paper (U.S. EPA, 2008) titled *Indoor Air Vapor Intrusion Mitigation Approaches* with detailed information for users. The U.S. EPA has also published a Technical Guide for assessing and mitigating the VI pathway (U.S. EPA, 2015). Naval Facilities Engineering Systems Command (NAVFAC) has developed VI mitigation fact sheets for new buildings (NAVFAC, 2011a) and existing buildings (NAVFAC, 2011b). Recent research sponsored by the DoD (ESTCP ER201322) demonstrated and validated a more rigorous and cost-effective process for design and optimization of systems for mitigating VI for VOCs.

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