Design Considerations Fact Sheet

ITRC has developed a series of fact sheets that summarizes the latest science, engineering, and technologies regarding the mitigation of vapors associated with vapor intrusion (VI). This fact sheet describes the most common design considerations for active mitigation systems, passive mitigation systems, and environmental remedial technologies that need to be considered as part of any design process.

1 INTRODUCTION

Multiple factors affecting the suitability and efficacy of a mitigation system should be considered during the design, review, and approval process, as discussed in this fact sheet. The selected technology should be based on a good understanding of the VI conceptual site model (VI CSM) (see ITRC ***Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet***) and able to meet the remedy objectives pertaining to soil vapor conditions at the site, whether applying an active system, passive system, rapid response, and/or an environmental remediation technology.

The design process should begin with a consideration of the VI CSM elements applicable to mitigation and the remedy objectives, leading to the design basis (i.e., an explanation of how the selected approach and technologies will meet the remedy objectives at the site). In many cases, this review indicates that additional information is needed for design of a specific type of mitigation system; therefore, the need for predesign investigations and/or testing should be considered. Once sufficient information is available for design, the next consideration is the design itself—the area that requires mitigation along with the system components, installation details, and specifications. Other design considerations include installation and operating permitting requirements; stakeholder requirements and communications; and the need for construction quality control, demonstration of system effectiveness and reliability, and operation, maintenance, and monitoring (OM&M) plans, including an exit or closure strategy.

Table 1-1 identifies the design considerations that are discussed in more detail below and evaluates their typical importance and impact on the design of an active (see ITRC ***Active Mitigation Fact Sheet)*** system, passive (see ITRC ***Passive Mitigation Fact Sheet*)** system, or an environmental remediation technology (see ***Remediation and Institutional Controls as Vapor Intrusion Mitigation Fact Sheet).*** Note that the importance of any factor can vary depending on site- and building-specific conditions and regulatory requirements.

Table 1-1 Summary of design considerations and impact on mitigation approach.

Design consideration	**Active approaches**	**Passive approaches**	**Remediation**	**Rapid response**
VI CSM considerations				
Vapor source and concentration				
Vapor source and concentration	●	●	●	◐
Geology and hydrogeology				
Subgrade soil type	●	◒	●	◒
Depth to groundwater/high water conditions	●	●	●	◐
Building conditions – new buildings				
New building	●	◒	◒	◒
Building conditions – existing buildings				
Foundation type(s)	●	◒	●	◒
Slab condition	◐	◒	●	●
Preferential pathways and utility penetrations	◐	●	●	●
Heating, ventilation, and cooling (HVAC) system	◐	◐	—	●
Height of building	◐	●	◒	◒
Historic building	◒	●	◐	◒
Building codes and industry standards	◐	◐	◐	◐
Design investigation and diagnostic testing				
Sub-slab diagnostic tests				
Pressure field extension (PFE) testing	●	—	●	◒
Differential pressure measurements	●	—	●	●
Barrier or liner material tests				
Diffusion coefficients	◒	●	◒	—
Building HVAC tests				
PFE testing/air flow rate testing/smoke tracer testing	◐	—	◒	●
Mitigation system design				
Design basis				
Design basis	●	●	●	◒
Design layout and components				
System layout	●	◒	●	◐

Table 1-1 Summary of design considerations and impact on mitigation approach.

Design consideration	**Active approaches**	**Passive approaches**	**Remediation**	**Rapid response**
System components	●	◐	●	●
Windows, air intake, and building exhaust	●	●	●	●
Permit requirements				
Installation permits	◐	◒	●	◒
Operational permits	◒	◐	●	◒
Stakeholder requirements				
Stakeholder engagement	●	●	●	●
Community engagement	●	●	●	●
System construction and implementation				
Construction oversight and quality control testing	◐	●	●	—
Smoke and tracer gas testing	◒	●	●	◐
System integrity testing	◒	●	◒	—
System effectiveness and reliability				
System effectiveness and reliability	●	●	●	●
Operation, maintenance, and monitoring considerations				
Operation, maintenance, and monitoring plans	◐	◐	●	●
Exit strategies				
Exit strategies	◐	◒	●	◐
Key | High impact ● | Medium impact ◐ | Low impact ◒ | Not applicable — |				

2 VI CSM CONSIDERATIONS

The design of a VI mitigation system should begin with a review of the existing VI CSM to ensure that the design will effectively address the VI pathway and achieve remediation objectives in an efficient manner consistent with the vapor source, site conditions, and building conditions. In many situations, this review is likely to identify data gaps that will require additional data gathering and predesign testing and revision to the VI CSM (see ***Conceptual Site Model for Vapor Intrusion Mitigation Fact Sheet***), as discussed in the next section. A summary of design considerations and their general impact on mitigation system design is provided in Table 1-1. The rationales behind these ratings are provided in the remainder of the fact sheet.

2.1 Vapor Source and Concentration

The approach and technology selected for vapor control at a site should take into account the compounds of concern (COCs), impacted media, and concentration ranges, as well as the location and depth of the vapor source(s).

For example, it may be possible to remediate the source of petroleum compounds quickly enough to address short-term VI risks. Similarly, technologies that promote the inflow of air (oxygen) below a building may enhance aerobic biodegradation of petroleum vapors before they reach the building. On the other hand, intrinsically safe equipment and combustible-gas monitors may be necessary if COC concentrations are in or near explosive ranges (e.g., methane due to biodegradation of petroleum compounds).

COCs sourced from solvent-impacted soil immediately below slabs may result in concentrations high enough to cause diffusion mass flux through intact slabs and even certain thin liners at rates sufficient to impact indoor air quality, even if the sub-slab region is actively depressurized. Vapors due to sources located outside of a building footprint may be intercepted before they migrate under the building. These are just a few examples of how the nature, magnitude, and location of the vapor source can impact mitigation strategy and technologies.

Active Mitigation	**High Impact:** Source mass controls the duration of operation, and source concentrations influence the target area to be contained. Discharge permits or off-gas treatment may be required for highly concentrated or large volume sources. High sub-slab concentrations may require diffusion control in addition to depressurization or venting.
Passive Mitigation	**High Impact:** Evaluation of which media are impacted, the COCs that pose an unacceptable risk to the subject building, the concentration range of each COC, and the location of the vapor source relative to the subject building are critical in the successful selection and implementation of an effective passive mitigation technology.
Environmental Remediation Technology	**High Impact:** The selection of the multiphase extraction (MPE) vs. soil vapor extraction (SVE) system is typically governed by the nature of the source (e.g., saturated vs. unsaturated zone). The type of COCs present determines the method of treatment of the extracted streams.
Rapid Response	**Medium Impact:** The COCs, concentration ranges, and location of source (particularly for large buildings) are very important for planning and selecting rapid responses measures. However, since rapid response efforts are typically focused inside the building, the media impacted and depth of the source outside the building envelope are of less concern.

2.2 Geology and Hydrogeology

Site geology and hydrogeology can affect the rate of COC migration in soil vapor toward and into buildings, depending on the nature and location of the vapor source, and remediation technologies that can be employed. Subsurface conditions can affect the efficacy of mitigation technologies that rely on vapor movement and/or the extension of negative pressure fields. Data on site geology and hydrology (e.g., soil moisture and porosity) to support the interpretation of soil gas profiles, the characterization of gas permeability, and the identification of anticipated soil gas migration routes in the vadose zone or the identification and characterization of impeded migration are important considerations in the design of any mitigation strategy, as discussed below.

Subgrade Soil Type: In most cases, the properties of soils immediately adjacent to the building (e.g., below the slab or next to foundation walls and footings) have the greatest impact on active mitigation technologies that require the movement of air and/or the propagation of vacuum below the slab. Soil type plays a major consideration for active mitigation strategies and makes some remediation technologies difficult to implement. For a more detailed description of methods to test and mathematically model the sub-slab permeability and transmissivity see (McAlary et al,, 2018). See Section J.2.5 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) for more information on the consideration of soil type in active mitigation.

Active Mitigation	**High Impact:** Permeability of the sub-slab fill material and underlying soil controls the pressure field extension (PFE) and air flow rates and, therefore, the degree to which sub-slab depressurization (SSD) and sub-slab ventilation (SSV) contribute to indoor air quality protection. This affects the spacing of suction points and fan size required to induce and maintain the negative pressure field beneath the structure.
Passive Mitigation	**Low Impact:** Passive mitigation systems typically incorporate a permeable layer beneath barriers and around vent piping in new construction. It may not be feasible to incorporate a permeable layer beneath an existing building. Therefore, passive venting systems function best in soils that are highly permeable when retrofitting an existing building.
Environmental Remediation Technology	**High Impact:** Remediation technologies require the characterization of soils beyond the subsurface to evaluate the effectiveness of the proposed technology. MPE and SVE are generally not applicable to low-permeability soils.
Rapid Response	**Low Impact:** Rapid responses typically include ventilation changes, indoor air treatment, or other efforts that are focused inside the building, therefore sub-slab conditions are not relevant.

Depth to Groundwater/High Water Conditions: Most active mitigation strategies require some type of air flow below the building slab; therefore, the presence or absence of shallow groundwater may play a key role in defining what technologies can be implemented. The presence of a sump pump may indicate that groundwater may be shallow and close to the building foundations and slab at certain times of the year. It may be possible to manage shallow groundwater, especially if it is either seasonally or occasionally present, by pumping the water or by gravity-feed siphon decanting. In many cases, sumps and associated sub-slab drainpipes can be incorporated into active depressurization systems, provided there is sufficient head space in the system to move air (USEPA, 1993).

Property owners may be able to provide observations of water entry or flooding that can be used to assess whether the planned mitigation system may become blocked during periods of high water; however, it is generally recommended that groundwater observations are made through a properly installed groundwater monitoring well.

Active Mitigation	**High Impact:** The presence of a sump pump in a building usually indicates the water table may be shallow at certain times of the year or during significant precipitation events. In locations where high water is present (e.g., a seasonal or temporary high-water table that intersects the slab) active mitigation systems may not be feasible without the water level being managed by pumping the water or by gravity-feed siphon decanting. Even with these management tools in place, water entrainment into the active mitigation system can cause damage to the system blower motor and impair the effectiveness of the mitigation system.
Passive Mitigation	**High Impact:** High water close to or in direct contact with the floor slab may limit the effectiveness of venting systems. For barriers to be effective they must be both waterproof and resistant to contact with chemicals.
Environmental Remediation Technology	**High Impact:** SVE is feasible only when sufficient unsaturated thickness is present. MPE can be applied at sites with or without unsaturated thickness; however, high groundwater increases the complexity and the OM&M requirements of the system.
Rapid Response	**Medium Impact:** Rapid responses typically include efforts that are focused inside the building, therefore sub-slab conditions are not relevant. However, sealing a sump or land drain system that is present to address high groundwater could be an effective rapid response measure.

See Section J.2.6 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) for additional discussion of considerations to be made where high water conditions may be present.

2.3 Building Conditions

The most important building factor affecting mitigation system design is whether it’s a new or existing building. A new building can largely be designed to incorporate the features required for efficient mitigation system operation, whereas mitigation system designers must generally work with (or around) existing building conditions. New building considerations are discussed first in this section, followed by a discussion of existing building considerations.

2.3.1 New Buildings

Mitigation systems can typically be incorporated into the design of new buildings, whether active, passive, or based on HVAC controls. With respect to active or passive systems requiring a sub-slab venting system, new construction should comply with current building codes and incorporate a “capillary break” below concrete floor slabs; i.e., 4 inches or more of coarse-textured granular fill to act as a drainage barrier to minimize water vapor diffusion through the concrete and avoid mold and damp rot issues. This may be adequately permeable for an SSD or SSV system; however, the mitigation system designer should specify a sufficiently permeable material to ensure adequate SSD/SSV performance over the long term.

While most new construction will include a moisture vapor barrier below the slab, typical membranes for this purpose may not be adequate for active mitigation systems and will generally not be adequate for mitigation systems relying on passive barriers. Therefore, the mitigation designer should specify a vapor barrier that meets the requirements of the mitigation system. The mitigation design should specify installation procedures that are consistent with intended construction procedures and reduce the potential for membrane damage during construction. For example, specify that concrete pours occur soon after membrane placement, prohibit vehicle traffic on the membrane, and specify that sharp objects be kept off the membrane. Additionally, if laser screed equipment is used during concrete pours, an adequate cushion layer (nonwoven geotextile, for example) may be required above the membrane to protect the membrane from the weight of the laser screed. The design should also specify that the contractor only turn the wheels on the laser screed when the unit is in motion to avoid unnecessary sheer strain on the membrane.

Designers of active or passive mitigation systems requiring vent riser pipes will typically need to work with the architect to ensure that suction pit, riser pipe, fan, and exhaust stack locations, dimensions, and materials are consistent with building use, aesthetics, and applicable building and fire codes. These and other design considerations for new buildings are provided in several industry standards, including ASTM and ANSI/AASRT (AARST, 2018a).

Designers should also consider whether passive systems could potentially require conversion to active systems based on performance monitoring (see ***OM&M/Exit Strategies Fact Sheet***) and, if so, how the design of the passive system can facilitate this conversion. Designs should consider more than just adding a fan to the vent stack(s). Designs may need to incorporate, among other things, size of building, air flow within the existing passive system, and the potential for short circuiting.

Active Mitigation	**High Impact:** Keys to success are a good quality floor and high permeability material below the floor, both of which can be accommodated in the building design and construction. The routing of passive ventilation stacks must be through the interior of the building and must be as straight as possible (i.e., no bends).
Passive Mitigation	**Low Impact:** Design of a passive vapor intrusion mitigation system (VIMS) in new construction allows for a high degree of control over

	variables that impact system performance, such as the building construction sequence and access during installation of the VIMS.
Environmental Remediation Technology	**Low Impact:** The SVE and MPE systems can typically be engineered to be compatible with the building features.
Rapid Response	**Low Impact:** Although rapid responses may initially not be applicable to new construction, installing an HVAC system with adequate outside air supply may be a useful supplement to another mitigation technique following start-up of the system.

2.3.2 Existing Buildings

Designs of mitigation systems for existing buildings are generally constrained by the construction materials used within and below the structure. The larger and more complicated a building, the more predesign work is likely to be necessary to characterize building and sub-slab conditions and create an effective system design. A building survey is typically conducted prior to the design of any mitigation strategy. A building survey will help select a mitigation technology that is appropriate for the building conditions and the CSM (see ***Conceptual Site Model for Vapor Intrusion Mitigation Fact Sheet***). Photographic documentation, a building sketch, and detailed notes should be included as part of the building survey. Attention must also be given to aesthetic restrictions established by building owners, zoning boards, and/or historic preservation entities that may limit exterior system components. A sample building survey form can be found in Appendix G of the ITRC VI guidance (2007): Vapor Intrusion Pathway: A Practical Guideline (ITRC, 2007a).

The following is a summary of items typically reviewed during a building survey and building information that needs to be considered to design an effective mitigation system.

Foundation Type: Basic foundation type has a direct impact on active and passive system designs. For example, SSD/SSV systems are applicable to basement and slab-on-grade construction, whereas sub-membrane depressurization (SMD) and/or other venting approaches are required for crawl space construction. Basements may require foundation wall mitigation in some cases, particularly if the source of vapors is beside the building. Many buildings (particularly larger commercial/industrial buildings) have multiple foundation types and locations due to building additions over time; slab and sub-slab conditions often vary between building areas, and foundation walls or changes in floor elevation may prevent airflow or PFE from one slab area to another. Other foundation features such as elevators, pits, sumps, utility tunnels, and other structures located below the slab or floor level may complicate mitigation designs. Regional construction standards, particularly in warmer climates and areas where large aggregate materials are expensive to source, may limit the viability of sub-slab mitigation systems.

Active Mitigation	**High Impact:** The construction and condition of building foundations have a significant influence on the effectiveness and viability of active mitigation.

Passive Mitigation	**Low Impact:** Passive mitigation systems can be tailored to different types of foundations.
Environmental Remediation Technology	**High Impact:** Deep foundations may affect soil vapor flow during SVE or MPE and necessitate that these systems be expanded.
Rapid Response	**Low Impact:** Rapid responses typically include efforts that are focused inside the building; therefore, foundation type is not relevant.

See Section J.2.4 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) for additional discussion of design considerations related to foundation types.

Slab Condition: Active mitigation systems typically rely on reasonable slab integrity to limit the flow of indoor air through the slab. Any downward airflow due to deteriorated or damaged slabs will reduce PFE and increase system airflow and, therefore, pipe and fan size requirements and energy costs (for fan operation as well as conditioning of replacement building air). In some cases, poor slab integrity can be addressed by replacing the slab or by placing a barrier or aerated floor over the slab. Even with reasonably intact slabs, some sealing of cracks and joints is typically required to optimize VIMS performance. The existing slab conditions should be noted in all areas of the building to be mitigated as well as the condition and the presence of cracks.

Active Mitigation	**Medium Impact:** Air leakage through breaks and cracks in the slab reduces the radius of influence (ROI) of an active mitigation system, and is an important parameter for selecting the number of suction points needed.
Passive Mitigation	**Low Impact:** This factor primarily applies to epoxy floor coatings with minimal impact on the effectiveness of barriers and venting systems.
Environmental Remediation Technology	**High Impact:** Highly fractured slabs may affect soil vapor flow during SVE or MPE and necessitate that these systems be expanded.
Rapid Response	**High Impact:** Floor slab crack, gap, or joint sealing can be an effective rapid response measure.

See Section J.2.4 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) for a summary of slab conditions or foundation conditions as they relate to mitigation design.

Preferential Pathways and Utility Penetrations: Preferential advective flow pathways through the building slab and foundation walls, if applicable, should be identified and plans to seal the pathways should be considered as part of the mitigation system design. Such openings may include utility penetrations, sumps, and/or the slab-foundation perimeter joint. Elevator shafts will need to be considered separately as they cannot be sealed (building codes require there to be a drain at the bottom of an elevator shaft, and this must not be sealed).

It should be noted that penetration sealing may have already been completed as part of rapid response actions at the site (see ITRC ***Rapid Response and Ventilation for Vapor Intrusion Mitigation Fact Sheet)*** or if a passive membrane is installed prior to active mitigation.

Active Mitigation	**Medium Impact:** Sealing potential preferential pathways will improve the efficiency and effectiveness of an active mitigation system by eliminating open vapor conduits into the structure, increasing the PFE, and reducing the amount of building air that is extracted and vented by the system.
Passive Mitigation	**High Impact:** Sealing around penetrations within the floor slab is critical to the effectiveness of passive mitigation systems.
Environmental Remediation Technology	**High Impact:** Sealing around penetrations within the floor slab may be critical to the effectiveness of SVE and MPE.
Rapid Response	**High Impact:** Sealing of preferential pathways and utility penetrations can be an effective rapid response measure.

See Section J.2.4 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) and Section 8 of AARST SGM-SF 2017 (AARST, 2017).

HVAC System: Evaluating the components, configuration, and operation of the HVAC system is an important step in the VI mitigation design process. Engineered HVAC adjustments can be considered as a component of VI mitigation by either (1) controlling cross-slab pressures by pressurizing the building, or (2) increasing air exchange rates (AERs). The size, age, and complexity of HVAC systems vary widely, from single family homes to large commercial/industrial buildings. Key aspects and components that should be assessed include number of units, airflow capacity, operating schedule/duty cycle (daily, weekly, seasonally), and other exhaust components that are not part of the HVAC system (e.g., exhaust fans in bathrooms, fume hoods in laboratories or kitchens, utility stacks). For more information refer to the ***Heating, Ventilation, and Air Conditioning (HVAC) Modification Technology Information Sheet***.

Active Mitigation	**Medium Impact:** An HVAC system may either enhance (i.e., create positive pressure and/or increase air exchange within the building) or impair (i.e., increase negative pressure within the building) active mitigation system performance.
Passive Mitigation	**Medium Impact:** An HVAC system may either enhance (i.e., create positive pressure and/or increase air exchange within the building) or impair (i.e., increase negative pressure within the building) passive mitigation system performance.
Environmental Remediation Technology	**No Impact:** HVAC modifications do not address/remediate the VOC source.
Rapid Response	**High Impact:** HVAC modifications can be an effective rapid response measure.

Building Height: The height of a building, as well as its height in relation to other surrounding buildings, plays a key condition in vent stack design and placement.

Active Mitigation	**Medium Impact:** Proximity of the exhaust point to occupiable areas, operable windows, or air intakes of surrounding buildings is an important consideration, especially where the emissions from

	the stack are high enough to sustain indoor air quality concerns considering the volume and air exchange rate of nearby buildings.
Passive Mitigation	**High Impact:** It is critical to consider vent stack placement in relation to entry points of surrounding buildings to ensure that effluent vapors do not enter adjacent buildings and that the system is able to vent.
Environmental Remediation Technology	**Low Impact:** Institutional controls (ICs) and SVE/MPE systems are typically not affected by the building height.
Rapid Response	**Low Impact:** Rapid responses typically include efforts that are focused inside the building; therefore, building height is not relevant.

Historic Buildings: Special considerations may be needed for mitigation system installation performed on historic buildings. In particular, the aesthetics of historic buildings may not only be important to the building owner or tenant but may also be guided by a historic preservation society. Installation may involve hiding system components behind false walls/cupboards and ensuring vent stacks do not break certain building sightlines.

Active Mitigation	**Low Impact:** Design of the overall system and specifically of exterior system components (blowers, pipes, and exhaust points) must consider aesthetics and historic building codes. Note that these restrictions do not alter the functional standards of the mitigation system.
Passive Mitigation	**High Impact:** Retrofitting passive mitigation systems in existing buildings may pose unique challenges to system design.
Environmental Remediation Technology	**Medium Impact:** SVE/MPE systems are generally temporary; however, they may need to be designed to be compatible with historic buildings.
Rapid Response	**Low Impact:** Rapid response measures can typically be implemented in historic buildings as they are in modern buildings.

Building Codes and Industry Standards:

The design of mitigation systems must consider the building codes, regulations, and standards that might apply. There are no overarching building codes for system construction that apply to every building in every state; however, municipalities may have requirements in their local building codes regarding system construction (material types, component locations, etc.). These codes should be reviewed and followed as applicable.

The radon mitigation industry has standards, which may provide useful information for design of VI mitigation systems, including recommendations on gravel size for venting media; gas conveyance pipe sizing, materials, and installation practices; vapor barrier materials and installation; exhaust vent configuration; vapor probe and other monitoring systems; and other criteria. The designer should exercise judgment in the application of radon standards, however, considering some of the differences in radon gas and chemical VI behavior and the degree of concentration reduction that may be required. In addition, new mitigation materials and technologies are being developed all the time, which may not be captured by existing radon or even VI guidance and standards.

Commonly used radon and soil gas standards include:

- ASTM E2121-13 - Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings
- AARST has standards for single-family, multifamily, schools/large buildings, and new construction. (ANSI/AARST: SGM-SF-2017 [AARST, 2017]; CC-1000-2018[AARST, 2018a]; RMS-MF-2018 [AARST, 2018b]; RMS-LB-2018[AARST, 2018c]). AARST is continually working to maintain and update these standards.

Active Mitigation	**Medium Impact:** Building codes and regulatory requirements must always be met, and at times will directly affect the mitigation approach. Radon standards have been established and updated for several decades and are an important tool in the mitigation design process. It is important to note that the radon standards are designed around mitigation of 100% of the occupied areas of the structure, which may not be necessary for point-source volatile organic compound (VOC) mitigation projects.
Passive Mitigation	**Medium Impact:** The degree to which local building codes affect passive mitigation system design varies from location to location and should be followed. However, local building codes do not exist in many locations.
Environmental Remediation Technology	**Medium Impact:** Building codes may impose certain restrictions on the construction of the SVE and MPE systems.
Rapid Response	**Medium Impact:** Some states may have rules or regulations on who can evaluate/modify HVAC systems to ensure they comply with building and energy code requirements.

3 DESIGN INVESTIGATION AND DIAGNOSTIC TESTING

Review of existing information and the VI CSM will often indicate the need for additional data gathering and/or design testing to develop the system design, including system location or layout, system components, and material specifications. Predesign tests commonly required for active, passive, and HVAC mitigation systems are discussed below.

3.1 Sub-Slab Diagnostic Tests

The most common sub-slab diagnostic tests conducted in existing buildings are pressure field extension (PFE) testing and measurement of differential pressures across the slab. These tests may also be conducted to evaluate the performance of mitigation systems installed in new construction.

PFE testing: PFE testing, also called ROI testing or communication testing, is conducted to understand the potential distance that differential pressure can be measured from a point of applied vacuum (a suction point), which is used to design the number of suction points and fan/blower size needed to achieve the desired system coverage. The PFE distance varies based on numerous factors—primarily the contrast in permeability between the floor slab and the material beneath the floor, as well as the underlying soils, but also including the location of building footers, floor drains, trenches, and utilities. Floor leakage may also be indicated by PFE assessments (i.e., areas of less than expected sub-slab vacuum could be near areas of air recharge across the floor slab). Active system design should consider the potential for PFE to vary due to soil drying and other factors that could change soil and building shell transmissivity over time.

Where PFE is not adequate to extend to all areas of potential concern, it may be appropriate to seal floor cracks, expansion joints, conduit openings, and joints around manhole covers to prevent short circuiting and improve efficiency of the active mitigation system. Where these pathways are inaccessible (under floor coverings, behind walls, etc.), additional suction points may be required. These pathways may have already been sealed during previous building mitigation activities (either previous rapid response activities or passive mitigation activities), but sealants are not always applied correctly, and vary in terms of their longevity, so it may be appropriate to reseal openings (see ***Passive Mitigation Fact Sheet*** or ***Rapid Response and Ventilation for Vapor Intrusion Mitigation Fact Sheet)***.

PFE testing is used in most commercial/industrial buildings to inform design of an SSD or SSV system (i.e., select the number and locations of suction points, fan sizes, etc.). Residential properties may not need a PFE test, if sufficient information is available to be reasonably confident in the mitigation system design (i.e., the slab is visible and in good condition and granular fill material is present below the slab). PFE testing on new construction may be performed during predesign activities to understand fan sizing but likely not to understand subsurface conditions as the engineered components are known and controlled during building construction. PFE testing is also not implemented for crawl space venting.

Active Mitigation	**High Impact:** PFE measurements have been the primary design metric for decades and are an integral part of the system design process. Additional testing options are also available (McAlary et al., 2018).
Passive Mitigation	**Not Applicable:** PFE testing is typically not considered in passive mitigation system design.
Environmental Remediation Technology	**High Impact**: PFE testing is crucial in confirming the effectiveness of the SVE and MPE systems in providing VI mitigation.
Rapid Response	**Low Impact:** Sub-slab depressurization is typically not a rapid response, therefore PFE is not relevant.

More information on PFE testing is included in AARST SGM-SF 2017 Section 6.2 (AARST, 2017) and more information on characterizing the transmissivity below the floor and the leakance of the floor is provided by ESTCP (McAlary et al., 2018).

Differential pressure measurements: The difference in pressures above and below the slab in existing buildings (the cross-slab pressure differential) is an indicator of the potential driving force behind the migration of soil vapors into buildings through joints, cracks, and other openings in the slab or foundation walls. To the extent the pressure is lower in the building relative to the sub-slab, this negative building pressure must be overcome by active systems based on sub-slab depressurization. It is important to note that in most buildings, the magnitude and direction of the pressure differential will vary over time due to changes in meteorological and building ventilation conditions, in both naturally ventilated buildings (most single-family homes) and in buildings with HVAC systems (many larger residential and commercial and industrial buildings).

Readings can be made with a digital micromanometer accurate to 0.25 Pa (0.001 inches H_20). Existing sub-slab sampling locations, or newly installed permanent test points, can be used to determine the vacuum across the slab. Enough locations should be installed and measured to be able to evaluate system effectiveness. PFE measurements should be collected at multiple radial distances from the suction points or sub-slab system piping to facilitate assessment of the trend of vacuum vs. distance. Variability in this trend should be evaluated prior to determining whether the system is affecting the area designated for mitigation. Where such locations are inaccessible, it may be valuable to use a combination of measurements from other areas and mathematical modeling to extrapolate system effectiveness (see McAlary et al., 2018 for examples). For SMD systems, the measurement of PFE may be taken only at location(s) farthest from the suction point, as long as the PFE is clearly measurable at that location.

Targeted differential pressure levels for design should provide a general factor of safety range to ensure depressurization is maintained under reasonably anticipated building conditions. A digital micromanometer can be used with data-logging capabilities to monitor cross-slab differential pressure to inform decisions on appropriate, building-specific target vacuum levels. Some states provide a guideline of generic values that generally range between a minimum of 1–6 Pa (example guidance documents with specified targeted differential pressures include New Jersey [NJDEP, 2018], Minnesota [MPCA, 2015], Massachusetts [MADEP, 2016], Pennsylvania [PADEP, 2019], and California [CalEPA, 2011]). For SSD, SSV, and SMD systems, levels of 1 Pa have been shown to be effective as long as it is maintained over time under normal building operating conditions (Lutes et al., 2011; Moorman, 2009). When soils under the slab are highly permeable, lower vacuums may be generated under high flow rate conditions, resulting in successful mitigation at differential pressure levels lower than 1 Pa (under normal building operating conditions). In these instances, the primary mechanism for system operation is likely SSV versus SSD. If lower vacuums are being observed under the slab in all or a portion of the designated mitigation area then other lines of evidence may be available to provide system verification (e.g., tracer testing, mathematical modeling, mass loading measurements, smoke pen, manual bubble flow meter, indoor air sampling) [McAlary et al., 2018]. More recent research also includes calculating PFE based on flux as another method to determine system effectiveness over the mitigated area (McAlary et al., 2020), though it may not be widely accepted by regulatory agencies.

There are often ambient fluctuations in the differential pressure across the floor slab caused by wind, mechanical fans, thermal gradients, etc., which create “noise” in baseline cross-slab vacuum measurements. It can be difficult to measure low levels of applied vacuum if there is substantial noise in the signal. A digital micromanometer with a datalogger can be used to make high frequency measurements of the baseline and characterize these fluctuations. Cyclic operation of the mitigation fan (on and off a few times) can create a characteristic saw-tooth pattern of drawdown and recovery that can be discerned from the noise in the baseline.

Some telemetry systems may also be able to measure and remotely monitor differential pressures. Telemetry systems, discussed in the operation, maintenance, and monitoring (OM&M) fact sheet, can be used to provide confidence in operating systems that are achieving lower levels of vacuum influence relative to baseline fluctuations or seasonal drift even if these values are lower than the applicable state's generic guidelines.

Active Mitigation	**High Impact:** The pressure differential is often the key parameter affecting the design, operation, and performance of an active system.
Passive Mitigation	**No Impact:** Differential pressure measurements are typically not considered in passive mitigation system design.
Environmental Remediation Technology	**High Impact:** Differential pressure testing confirms the effectiveness of the SVE and MPE systems in providing VI mitigation.
Rapid Response	**High Impact:** Differential pressure is the primary performance metric for rapid response measures that include modifying HVAC systems to pressurize a building.

3.2 Barrier or Liner Material Tests

VI barrier materials, such as membrane or spray-on liners, are often a key component of both passive and active systems. The required barrier properties depend on the barrier function, and other factors discussed in the following section. When the barrier is required to control diffusion of VOCs, it may be necessary to perform tests to determine the diffusion coefficient of the barrier, if not available from the barrier manufacturer.

Diffusion Coefficients: Standard ASTM methods used to calculate water vapor permeation (ASTM E96) can be rudimentary when water is replaced with COCs. Water vapor tests are not appropriate due to their inability to monitor challenge concentrations (the side of the testing chamber containing COCs). However, more nuanced testing methodologies have been developed to more accurately calculate diffusion coefficients for passive barriers. While there is not a universal testing standard, best practices for testing method reporting should include a mass flux rate (m^2/sec), barrier sample thickness, test duration, and challenge concentration. Manufacturers of VI barrier products should publish diffusion test results and these testing results should be evaluated on their own merits. While testing methodologies can vary between manufacturers, there are independent laboratories and universities using standard protocols to determine chemical diffusion rates for various commercially available passive barriers. When selecting a passive barrier system, diffusion coefficients established for specific barrier products should be assessed to determine if they are capable of providing an adequate level of protection against COC concentrations present within the vapor source.

Active Mitigation	**Low Impact:** This is primarily a concern where sub-slab concentrations are very high or a vapor membrane is installed in conjunction with the active system.
Passive Mitigation	**High Impact:** Diffusion coefficients can be a good indicator of a product's ability to be protective against COCs.
Environmental Remediation Technology	**Low Impact:** SVE/MPE systems typically generate high flow rates, with advective effects dominating.
Rapid Response	**Not Applicable:** Backdraft testing is not typically relevant to rapid response.

3.3 Building HVAC Tests

Differential Pressure Measurements: PFE testing can be used to assess the impact an HVAC system has on the cross-slab pressure gradients, as also discussed in Section 3.1. Depending on the operation of the HVAC system, the building space may be pressurized or under vacuum in comparison to sub-slab conditions. To test the cross-slab pressure gradients, differential pressure readings can be recorded using digital micromanometers connected to sub-slab monitoring ports while the HVAC system operates at different conditions.

Air Flow Rate Testing: Air flow rates can be recorded at HVAC intakes and exhausts to quantify AER within a building. These readings are typically collected using a digital anemometer placed at the intake and exhaust points of an HVAC system. This information can help determine if supply or return air flow rates need to be adjusted to accomplish the desired AER or pressure within a building.

Smoke Tracer Testing: Smoke tracer testing involves the use of smoke to evaluate the air flow paths within a building due to HVAC operations. This can be helpful in evaluating how the impacts of VI in one area of a building may affect other areas. Smoke tracer testing can be completed by releasing a small amount of smoke or other visible vapor or powder into the indoor air and observing its flow path visually. This process can be completed at various HVAC operating conditions to compare its impact on the flow of indoor air.

Active Mitigation	**Medium Impact:** PFE testing is of high importance to the design of SSD systems, as described in Section 3.1, but other building tests may also have a significant impact on active system design.
Passive Mitigation	HVAC typically has **little to no impact** on design of passive mitigation systems.
Environmental Remediation Technology	**Low Impact:** SVE/MPE systems typically rely on relatively high vacuum and soil vapor flow rates; therefore, operation of the building HVAC system has limited impact on their effectiveness.
Rapid Response	**High Impact:** HVAC modification is one of the primary rapid response approaches that can be implemented. Therefore, conducting building HVAC tests to fully understand system characteristics, capacities, etc., is critically important.

4 MITIGATION SYSTEM DESIGN

Key considerations related to mitigation system design include the design basis, the system layout and components, permit requirements, and stakeholder requirements, as discussed below.

4.1 Design Basis

The mitigation system design should include a design basis document that explains how VI is occurring (or could occur in new buildings) based on the VI CSM (see ITRC ***Conceptual Site Models for Vapor Intrusion Mitigation Fact Sheet)*** and how the mitigation approach and technologies selected will control VI sufficiently to meet the remedy objectives. For example, if VOCs are entering the building by advective flow of soil vapor through cracks and other openings in the slab, the design basis should show how these entry points will be controlled, e.g., through passive barriers (see ITRC ***Passive Barriers Technology Information Sheet)*** and/or active depressurization (see ITRC ***Sub-slab Depressurization Technology Information Sheet***). The design basis should indicate whether VOC concentrations below the slab are high enough to cause VI by diffusion through the slab and, if so, how the diffusion pathway will be controlled. Similarly, the design basis should indicate how any preferential pathways will be controlled. If HVAC and/or indoor air treatment technologies are selected, the design basis should demonstrate that indoor air concentrations can be reduced sufficiently to meet remedy objectives (unless used solely as a rapid response, in which case, partial reduction of indoor air concentrations may be an acceptable short-term objective).

The design of a mitigation system or an environmental remedy intended to control VI will depend in part on the remedy objectives, typically related to applicable regulatory requirements. The technology selected must be capable of reducing indoor air concentrations, for example, below target levels, within an acceptable time frame, for as long as required.

The design basis document should also identify additional information needed to complete the design, such as predesign inspections, surveys, and testing, and how the performance of the system will be measured to demonstrate that remedy objectives are met initially and over the long term. The design considerations pertinent to predesign testing, the layout and components of the design, construction quality control, system OM&M, and ultimate system closure are discussed in the following sections.

Active Mitigation	**High Impact:** The design basis is critical to all long-term mitigation system designs.
Passive Mitigation	**High Impact:** The design basis is critical to all long-term mitigation system designs.
Environmental Remediation Technology	**High Impact:** The design basis is critical to all long-term mitigation system designs.
Rapid Response	**Low Impact:** The design basis is less important for rapid response, as these actions are generally based on presumptive actions that will typically lessen the impacts of VI but are not necessarily expected to meet long-term remedy objectives.

4.2 Design Layout and Components

Mitigation system designs will commonly include one or more layout sheets, showing where the various components of the system will be placed in, below, or around the building; detail drawings showing how system components will be configured in specific areas; and the components' dimensions, materials, and other specifications. A number of things should be considered associated with the system layout and component specifications.

System Layout: Whether a new or existing building, the system should be placed where needed to prevent VI from occurring. This relates to the VI CSM and the location of vapor sources and vapor entry points (particularly for existing buildings), as well as the design basis for controlling vapor entry. For active systems, the points where pressure differentials are applied and the ROI determine the system coverage. For passive systems, the barrier must cover the area of potential vapor or VOC (i.e., by diffusion through slabs or foundation walls) entry. For HVAC systems, positive pressure and/or ventilation must occur in rooms that will be affected by VI, which can include areas well beyond the vapor entry points.

Active Mitigation	**High Impact:** The selection of the mitigation blower(s) and the number and locations of suction points are key design parameters. The selected mitigation fan can directly impact the diameter and amount of system piping. Discharge stacks must be located to avoid re-entrainment and fans located to maintain negative pressure on components inside the building.
Passive Mitigation	**Low Impact:** System design is generally consistent underneath the entire building foundation.
Environmental Remediation Technology	**High Impact:** Proper SVE/MPE system layout is essential to ensure that these systems can serve as means of VI mitigation.
Rapid Response	**Medium Impact:** Although the design phase of a rapid response is typically very abbreviated, consideration should be given to the location where rapid response measures are implemented. For example, the layout of the existing HVAC system, locations of doors and windows, and the location of preferential pathway sealing and placement of indoor air treatment units are critical.

System Components: The system components include materials such as permeable sub-slab gravel layers; gas conveyance and riser pipes; liners for both active and passive systems; and fans and monitoring equipment for active systems (although both may include many additional components). The design should include the standard components recommended by applicable standards and guidance documents; therefore, reference to such documents is something a reviewer should look for. Similarly, the type, material, size, dimensions, and spacing of system components should be based on standard practice and/or design calculations, showing the components will provide sufficient performance to meet design objectives. Further, the design drawings and/or specifications should indicate how materials should be installed, the codes that should be met, and the quality control testing required to confirm proper materials and installation.

Active Mitigation	**High Impact:** System performance depends on selection of adequate components. Fan selection depends primarily on the permeability of the material below the floor, suction point spacing, pipe friction losses, and the required negative pressure. Alarms, placards, telemetry, and performance monitoring infrastructure are important to ensure system reliability. Barriers are generally required to reduce downward air flow through the floor and reduction in system efficiency, although they also may serve to minimize upward soil vapor flow for short time periods if systems shut down.
Passive Mitigation	**Medium Impact:** System components should be identified and located on mitigation system design sheets. System components such as vent riser pipe should be spaced and placed uniformly underneath the entire building foundation to ensure adequate coverage.
Environmental Remediation Technology	**High Impact:** Specifying proper components of SVE/MPE system layout is essential to ensure that these systems can serve as means of VI mitigation.
Rapid Response	**High Impact:** Selecting the property equipment and materials for a rapid response is critical. Examples include selecting appropriate sealants for cracks and preferential pathways and properly sized indoor air treatment equipment.

Windows, Air Intake, and Building Exhaust: The location and configuration of active (and to a lesser degree, passive system) vent stacks is critical to prevent inadvertent re-entrainment of exhausted vapors back into the building. The radon industry has developed recommended distances between exhaust points and building entryways (doors, windows), as described in existing industry guidance (e.g., AARST, 2018a), as well as in some state VI guidance. Typically, vent stack locations are not less than 2 feet above or not less than 10 feet horizontal distance away from openings (windows, doors, etc.) and not less than 30 feet away from mechanical equipment air intakes, although building- and site-specific conditions, as well as local codes and regulations, may result in different requirements. For many VOCs, the indoor air screening levels are very low, and it may be necessary to have taller stacks or larger separation distances to avoid re-entrainment of VOC vapors from the effluent to indoor air. In some cases, air dispersion modeling may be useful to help appropriately place a vent stack for a system.

The top of the vent stack discharge pipe should typically be vertical or as close to vertical as possible (not more 45 degrees from vertical) (AARST, 2018a). Rain caps are often not necessary or recommended, but if rain caps are used, they should not impinge on the vertical discharge of vapors from the stack. See Section J.3.3 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) and ANSI/AARST: SGM-SF-2017 (AARST, 2017); CC-1000-2018 (AARST, 2018a); RMS-MF-2018 (AARST, 2018b); RMS-LB-2018 (AARST, 2018c).

Active Mitigation	**High Impact:** Impact depends on the mass loading: if the emission rate is small, the risk of significant re-entrainment is also small. Where the emission rate is high, a taller stack, greater distance from re-entrainment points, or off-gas treatment may be needed.

Passive Mitigation	**High Impact:** Vent stack placement is critical to ensuring effluent vapors do not enter adjacent buildings.
Environmental Remediation Technology	**High Impact:** Placement of the SVE/MPE system discharge is critical to ensuring that system exhaust does not enter buildings.
Rapid Response	**High Impact:** Rapid response measures typically do not include vent stacks; however, the location of windows, fresh air intakes, and other building exhausts are important considerations for rapid response measures such as ad hoc ventilation and HVAC modification.

4.3 Permit Requirements

Mitigation system designs must consider building codes, including radon requirements if applicable, and other permits that need to be addressed, depending on the type of system and design, including installation permits and operating permits.

Below is a description and more information on permits that may need to be considered prior to, during, or immediately before system construction.

Installation Permits: Some municipalities may require a building permit or electrical permit for system installation. A person should check with the local municipality prior to installation for requirements. In some states, subsurface mitigation systems may be exempt from or do not require installation permits. More detail is provided in Section J.3.2 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014).

Active Mitigation	**Medium Impact:** State, local, and federal permitting requirements need to be reviewed during the design phase, and any relevant requirements should be incorporated into the design. Typically, there are few installation permit requirements that will significantly affect an active mitigation design, especially on a typical residential property.
Passive Mitigation	**Low Impact:** Permits are typically not required for the installation of passive mitigation systems. Confirm installation permit requirements with your state and local regulatory agencies and the building department of your local unit of government.
Environmental Remediation Technology	**High Impact:** Most SVE/MPE systems include treatment and discharge, as well as electrical and plumbing work, and therefore require that relevant permits be secured.
Rapid Response	**Low Impact:** Due the expedited nature, permitting is typically not relevant for a rapid response, although close regulatory stakeholder engagement is recommended.

Operational Permits: As detailed in Section J.3.2 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014), air permits and emission controls on active mitigation systems must be considered for each project based on the system design, the conceptual site model, and the applicable state, federal, or local regulations. The regulations are generally associated with the Clean Air Act or local ordinances that have been set by statute. In some states, subsurface mitigation systems may be exempt from or do not require permits. More detail is provided in Section J.3.2 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014).

Active Mitigation	**Low Impact:** Emissions from individual active systems are often below minimum thresholds for air discharge permits. For larger sites with multiple active systems, the mass removal rate should be determined. The required permits for the system should be obtained if discharge volumes and concentrations indicate the need.
Passive Mitigation	**Medium Impact:** Permits are typically not required for the installation of passive mitigation systems. However, consideration should be given to applicable emission permits required by your state and local regulatory agencies.
Environmental Remediation Technology	**High Impact:** Discharge permits are typically required to operate the SVE and MPE systems.
Rapid Response	**Low Impact:** Due to the expedited nature, permitting is typically not relevant for a rapid response, although close regulatory stakeholder engagement is recommended.

4.4 Stakeholder Requirements

Owners, tenants, and other parties (including contractors and architects for new buildings) often have strong opinions about the aesthetic effects and inconvenience experienced with the location of mitigation system components, including fans, pipe runs, and vent stacks. Stakeholders should be engaged, and their considerations incorporated into the system design as early as practical.

Stakeholder Engagement: To ensure that stakeholder concerns and requirements are addressed early in the design process, the building owner, tenant, and other parties in the building should be provided with information regarding the mitigation system installation activities. Common items may include:

- basic description of mitigation system (components, operation, etc.) to be installed
- photos of typical system components to be expected
- length of time for system installation and start-up
- any restrictions to access or use to portions of their property during system installation
- potential noise level from construction activities that may be expected with system installation (if anticipated to be disruptive to the building occupants)
- other building activities that may need to be completed for system installation to be possible (e.g., a furnace needs to be raised to access the basement floor or a staircase needs to be fixed so that the basement can be accessed safely by the workers). These activities may be part of the installation activities completed by the responsible party.
- contact information if issues or questions arise during the mitigation system installation.

The ITRC ***Public Outreach During Vapor Intrusion Mitigation Fact Sheet*** provides additional information for plan communications with property owners and building occupants.

Communication with the property owner on their expectation of the design, if any, early in the design process will help to avoid problems during installation and operation. Homeowners should be made aware of the need for and importance of ensuring proper function of the mitigation system. Items such as possible piping locations, blower locations, power use, how modification to the building may affect the performance of the mitigation system, and future system OM&M (incorporation of certain types of telemetry in the design may limit or reduce the need for frequent property visits) should be discussed in the design phase. Considerations should also be made to address the potential for noise issues for the building occupants, depending on the type and locations of blowers planned for the design.

Active Mitigation	**High Impact:** Owner, tenant, and stakeholder engagement is a critical part of any active mitigation response.
Passive Mitigation	**High Impact:** Owner engagement is a critical part of the implementation of a passive mitigation system. Contact your state and local regulatory agencies to confirm your regulatory obligations with respect to notification requirements.
Environmental Remediation Technology	**High Impact:** Implementation of the SVE/MPE typically involves an extensive interaction with the property owners, including access agreements.
Rapid Response	**High Impact:** Owner, tenant, and stakeholder engagement is a critical part of any rapid response.

Community Engagement: In many cases where multiple buildings are involved, the larger community and other stakeholders should be engaged as early and often as possible. Contact your state and local regulatory agencies to confirm your regulatory obligations with respect to notification requirements. See the ***Public Outreach During Vapor Intrusion Mitigation Fact Sheet*** for more information.

Active Mitigation	**High Impact:** Community engagement is a critical part of any active mitigation response that may impact multiple parties beyond the owner/occupant of the property.
Passive Mitigation	**High Impact:** Community engagement is a critical part of the implementation of a passive mitigation system, especially if the rapid response is large scale or highly visible.
Environmental Remediation Technology	**High Impact:** Implementation of SVE/MPE typically involves an extensive interaction with the stakeholders, including discussions about such issues as the effect of the system noise and treated air stream discharge.
Rapid Response	**High Impact:** Community engagement is a critical part of any rapid response, especially if the rapid response is large scale or highly visible.

5 SYSTEM CONSTRUCTION AND IMPLEMENTATION

The mitigation design should include requirements for construction quality control, including observation and inspection and quality control testing requirements.

5.1 Construction Oversight and Quality Control Testing

Quality control and assurance procedures should be selected during the design phase of a mitigation system in order to ensure these procedures will be incorporated during the construction process. The manufacturer's requirements, regulatory requirements, and site-specific needs should be considered when selecting which system integrity testing methods to use.

After the VIMS design has been developed and documented, the engineer of record or equivalent should confirm that a preconstruction meeting is planned with all persons involved with the installation of the VIMS, as well an any subcontractors whose work may affect the performance of the VIMS during and/or following the installation process. This may include, but is not limited to the architect, engineer of record, environmental consultant, general contractor, mitigation system installation contractor, and concrete contractor, including the rebar installer, electrician, and plumber. The purpose of this meeting is to inform all contractors involved of the purpose and importance of the VIMS. During this meeting, all parties in attendance should review the VIMS installation drawing set to confirm that the details shown in the drawings match the project conditions. This allows all contractors to review and confirm substrate specifications, vent layout, and locations of vent risers and utility penetrations, and allows the general contractor to clarify the construction/installation sequence with all trades. Once all site conditions are confirmed, action items should be created that address any conditions not reflected in the project drawings.

Installation oversight will vary depending on local building code and regulatory requirements. Frequency and duration should be specified in the VMS plan, but providing oversight prior to installation and during installation will increase the likelihood that the system is installed per plans and specifications. Oversight documentation will provide a record for future building occupants and operators.

For installation of any type of active mitigation system, it is important that properly trained and licensed, if necessary, technicians provide construction quality assurance (CQA) during installation of mitigation system components. The mitigation system design should provide for typical CQA tasks, such as the following for active and/or passive systems:

- review and approval of applicable submittals, including gravel specification; membrane (and membrane adhesives, mastics, etc.); aerated slab forms; pipe and fittings; system monitors and alarms; and fan(s)
- inspection of system components, including gravel placement, piping/vent strips, membrane, and aerated floor; membrane penetrations and boots; slab placement; riser and conveyance pipes; fans; and system monitors and alarms
- Although CQA is always important for any project, the level and formality of CQA completed will depend on the size and complexity of the building and associated system to be constructed.

Active Mitigation	**Medium Impact:** Impact of the need and details of construction quality controls will depend of the size and complexity of the

	system. Typical designs on residential properties will need few construction quality control considerations, but large building designs may require several discussions and meetings to finalize the design. The performance of active systems can often be enhanced after initial installation, if necessary, by increasing fan capacity or adding suction points.
Passive Mitigation	**High Impact:** It is usually difficult to modify passive systems after installation. It is critical to ensure a preconstruction meeting is planned with all persons involved with the installation of the VMS, as well an any subcontractors whose work may affect the performance of the VMS during and/or following the installation process.
Environmental Remediation Technology	**High Impact:** Construction QA/QC is a key element of the installation process of the SVE/MPE systems.
Rapid Response	**Not applicable**

Smoke and Tracer Gas Testing: Smoke and tracer gas testing is an option to test system air flow patterns. For example, if smoke is drawn below the floor strongly through an open sub-slab port during SSD/SSV operation, this indicates the system is effective (in cases where the material below the floor is highly permeable, this can occur where the applied vacuum is too low to measure even with a digital micromanometer). A smoke pen can also be used at known or suspected cracks and preferential pathways across the floor or building envelope or to verify a membrane is adequately sealed to the building walls (SMD). Radon may also be used as a tracer gas in some situations where it is naturally present at sufficient levels to measure in both indoor air and sub-slab soil gas, as a semi-quantitative indicator of system attenuation (radon and COC source and transport conditions may be different).

Helium can be used in at least two ways as a sub-slab gas flow tracer. An interwell test consists of adding a few liters of helium to a probe at some distance (e.g., 5–15 ft) from a suction point and monitoring the concentration of helium in the extracted gas at the suction point. A helium flood consists of reversing the mitigation system flow direction and blowing air with about 1% helium added into the subsurface and monitoring the arrival of helium at various sub-slab probe locations. More information can be found in Section J.4.3 of ***Appendix J in the 2014 ITRC PVI document*** (ITRC, 2014) and ESTCP (McAlary et al., 2018).

Smoke testing for passive barriers is the process of injecting nontoxic smoke underneath the barrier, checking for any smoke penetrating the barrier, and then patching the barrier to ensure no more smoke penetrates the barrier. Smoke testing can be applied to any type of passive barrier system by injecting through a passive vent riser or by cutting a hole within the passive barrier system to inject the smoke. Smoke testing should be performed on predetermined intervals until the entire system is tested.

Active Mitigation	**Low Impact:** Smoke and/or tracer gas testing can confirm the effectiveness of active mitigation systems but should not be the sole verification method of system effectiveness or function.

Passive Mitigation	**High Impact:** Smoke and/or tracer gas testing is a highly effective way to confirm the integrity of a passive mitigation system without the need to add penetrations to mitigation systems.
Environmental Remediation Technology	**High Impact:** Smoke and/or tracer gas testing is a highly effective way to confirm the effectiveness of SVE/MPE as VI mitigation measures.
Rapid Response	**Medium Impact:** Smoke testing can be used to demonstrate building pressurization at windows and doorways.

System Integrity Testing: Passive barriers are constructed in the field and applied prior to placing a concrete slab. Each barrier system should have installation specifications along with quality control procedures to test the integrity of seams, seals around penetrations, system termination points, and overall field membrane integrity. Quality control procedures can vary based on the passive barriers selected, but common procedures include smoke testing, coupon sampling, air lancing, and seam probing. For more information refer to the ***Passive Barrier Technology Information Sheet***.

Active Mitigation	**Low Impact:** Integrity testing would apply to active mitigation systems if a vapor membrane is installed in conjunction with the active system, although membranes primarily affect system efficiency rather than performance, if pressure differential requirements are met.
Passive Mitigation	**High Impact:** Thickness verification is important to confirm proper installation of passive mitigation systems. It is recommended to follow the product manufacturer's guidance on frequency of coupon sample collection.
Environmental Remediation Technology	**Low Impact:** SVE and MPE used for VI mitigation generally do not include barriers under existing buildings.
Rapid Response	**Not Applicable**

5.2 System Effectiveness and Reliability

Once a system is installed, inspections and testing are typically required to "commission" the system—that is, to confirm that the system is meeting performance criteria and remediation objectives. Consideration as part of the design process should evaluate the potential that the system will be effective and that it can be reliably maintained both in the short and long term. The design should consider and specify common testing to be conducted after installation to demonstrate system effectiveness and reliability, depending on the type of system installed. Active mitigation systems will typically require measurement of system vacuum and air flow, cross-slab pressure differentials, and potentially COC concentrations in exhaust gases (e.g., for air quality permitting purposes). Active and passive systems may require sub-slab, indoor air, and outdoor (ambient) air testing to demonstrate performance, particularly when the system is first commissioned. More information on testing to verify system effectiveness and reliability is provided in the ***Post-Installation System Verification Fact Sheet***.

Active Mitigation	**High Impact:** Demonstrating the effectiveness and reliability of active systems after installation is critical.

Passive Mitigation	**High Impact:** Demonstrating the effectiveness and reliability of passive systems after installation is critical.
Environmental Remediation Technology	**High Impact:** Demonstrating the effectiveness and reliability of environmental remediation to also mitigate VI is critical.
Rapid Response	**High Impact:** Demonstrating the effectiveness and reliability of HVAC controls is critical. The need to demonstrate the effectiveness and reliability of rapid response actions depends on the situation.

5.3 Operation, Maintenance, and Monitoring Considerations

The mitigation system design should consider and include post-installation OM&M requirements, commonly provided in an OM&M plan, which provides instructions for system operation and upkeep. An OM&M plan should be prepared for each installed mitigation system. Consideration of the OM&M must occur during the design phase. As part of the design, the ease of performing the OM&M activities must be considered. For example, if a monitoring system consistently requires a homeowner to access a location that is not easily accessible (e.g., their attic to monitor if a fan is running), there is a greater chance that the system will not be maintained or monitored.

Details of a typical OM&M plan can be found in Section 6.3 and Section J.3.2 in the ***2014 ITRC PVI document*** (ITRC, 2014) and are further provided in the ***OM&M/Exit Strategy Fact Sheet***.

Active Mitigation	**Medium Impact:** Most fans designed for radon-style mitigation have a long service life. An automated alarm can be used to identify the need for fan service or replacement. Monitoring needs vary, depending on the source strength, building occupancy, and local regulatory requirements. Consider also periodic collection of data that may be needed to support closure in the future.
Passive Mitigation	**Medium Impact:** During the design phase, consideration should be given to state regulatory requirements regarding ongoing operation and maintenance of a passive mitigation system. Contact the applicable state regulatory agencies to confirm your regulatory requirements.
Environmental Remediation Technology	**High Impact:** MPE and SVE systems require that OM&M be performed on a regular basis to ensure effectiveness, conduct repairs, and ensure that the treatment of the extracted media remains in compliance with the permit requirements.
Rapid Response	**High Impact:** Although rapid response measures by their nature are limited in duration, operation and maintenance are critical during deployment.

5.4 Exit Strategies

The mitigation system design should consider what information and criteria are needed to allow orderly and safe shutdown of the system at the appropriate time. The criteria for shutdown should be based on the VI CSM and design basis, and the OM&M plan should result in the collection of data necessary to determine when shutdown can occur. More information on exit strategies can be found in the ***OM&M/Exit Strategies Fact Sheet***.

Active Mitigation	**Medium Impact:** During the design process step in an active mitigation approach, it is important to understand the potential time frame over which the system may operate and what a potential exit strategy may look like.
Passive Mitigation	**Low Impact:** Passive mitigation systems will continue to function regardless of whether a vapor source has biodegraded or has been remediated and no longer poses an unacceptable risk.
Environmental Remediation Technology	**High Impact:** SVE/MPE systems are typically operated for a limited time; therefore, a clear exit strategy must be developed.
Rapid Response	**Medium Impact:** Rapid response measures are limited in duration and are implemented ahead of a long-term mitigation approach. It is important to clearly define and communicate the transition process from rapid response measures to long-term response actions.

6 SUMMARY

The design of a VI mitigation system should consider a variety of factors to ensure that the design is consistent with and will adequately address the VI pathway, including a review of the VI CSM and source, site, and building conditions that could impact mitigation strategy and design; the potential need for additional design investigations and mitigation diagnostic testing; and the appropriate locations and components of the mitigation infrastructure (i.e., the system layout and specifications). The design should also include various plans to ensure the proper construction, installation, and operation of the system, including a CQA and control plan; procedures to confirm that the system is meeting performance objectives and criteria when first installed; an OM&M plan; and potentially other plans, depending on the nature of the system and regulatory requirements.

Building structures vary widely in their size, function, and use; therefore, the implementation of mitigation technologies will vary widely, depending on the type of building for which the active system is needed and the intended design objectives of the system. This fact sheet summarizes the many considerations that go into the design, installation, verification, and operation of each of the most common mitigation technologies as they relate to some of the more common building types and uses.

7 REFERENCES AND ACRONYMS

The ITRC VI Mitigation Training web page includes lists of acronyms, a full glossary, and combined references for the fact sheets. The user is encouraged to visit the ITRC VI Mitigation Training web page to access each fact sheet and supplementary information and the most up-to-date source of information on this topic.