United States Environmental Protection Agency

Engineering Issue

Indoor Air Vapor Intrusion Mitigation Approaches

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1 PURPOSE

The U.S. Environmental Protection Agency (EPA) Engineering Issue in one of a new series of technology transfer documents that summarize the latest available information on selected treatment and site remediation technologies and related issues. The Engineering Issues are designed to help remedial project managers (RPMs), on-scene coordinators (OSCs), contractors, and other site managers understand the type of data and site characteristics needed to evaluate a technology for potential applicability to their specific sites. Each Engineering Issue document is developed in conjunction with a small group of scientists inside the EPA and with outside consultants and relies on peer-reviewed literature, EPA reports, Web sources, current research, and other pertinent information. The purpose of this document is to present the "state of the science" regarding management and treatment of vapor intrusion into building structures.

Wherever feasible, this information relies on independently reviewed mitigation performance information. In an effort to keep this Engineering Issue paper concise, important information is summarized, while references and Web links are provided for readers interested in additional information; **these Web links, verified as accurate at the time of publication, are subject to change.** Although we have endeavored to make these links fully functional with a mouse click, if they do not function on your system, you may need to copy them into your browser or reenter them. As science and technology associated with this route of exposure continues to develop, other mitigation measures may become available.

2 INTRODUCTION

2.1 Subject and Intended Audience

Vapor intrusion is defined as the migration of volatile contaminants from the subsurface into overlying buildings. Volatile contaminants from buried wastes and/or contaminated groundwater or soil can migrate through subsurface soils and into indoor air spaces of overlying buildings. The vapor intrusion risk pathway may be important for buildings with or without a basement (EPA, 2002a).

Vapor intrusion issues are widespread; for example, as of March 15, 2006, there were 268 site investigations in the State of New York and mitigations were underway or completed at 72 of those sites

(Anders, 2006). Similar studies and mitigations have been carried out in a large number of the states.

This paper is focused on the **mitigation** of vapor intrusion to prevent human exposure to anthropogenic soil and groundwater contaminants. This document is designed to provide sufficient information to allow the reader to understand the range of mitigation technologies available. The document also provides information on selecting appropriate technologies in consultation with qualified engineering and risk management professionals. The intent is not to provide detailed engineering protocols, nor to provide lists of vendors. Rather, it is intended that the reader will be generally informed to make appropriate selections, and to evaluate the recommendations of mitigation contractors and engineers.

The primary target audience for this paper includes EPA staff, regional program offices, RPMs and state government environmental staff. Others who may be interested in this document may include:

- Engineering consultants
- Building professionals, including architects, property developers, contractors and engineers
- Health and safety/industrial hygiene specialists
- Stakeholder groups and the general public

Because of its concentration on vapor intrusion mitigation, this paper will not directly consider the following.

Characterization and Risk Assessment Techniques

Vapor intrusion is typically first evaluated with characterization measurement and risk assessment techniques. This document will not provide much discussion of these topics, which are covered in EPA's draft vapor intrusion guidance document (EPA, 2002a; at http://www.epa.gov/correctiveaction/eis/vapor/complete.pdf) and are expected to be the subject of an upcoming revised guidance.[1] The reader should therefore consult the EPA guidance and other appropriate documents [for example, Interstate Technology and Regulatory Council (ITRC) at http://www.itrcweb.org/Documents/VI-1.pdf and http://www.itrcweb.org/Documents/BRNFLD-1.pdf] for information on issues such as fate and transport of volatile organic compounds (VOCs) in the subsurface, assessment methods, risk assessment, and regulatory standards. Much of the regulatory authority in this area resides with the individual states.

Rather, this paper is focused on solutions that can be implemented once an unacceptable risk from vapor intrusion is determined to exist, or as precautionary measures. As further discussed below, the type of control implemented will be based on many factors including site use, amount of impact, cost, and regulatory acceptance, but can be generally broken into two classes of solutions: source control and controls implemented at the structure.

Remediation

Remediation in the plumes or at the sources will eventually mitigate potential exposure pathways and can include any of the following:

- Removal of contaminated soil (typically for off-site treatment) and groundwater (typically for ex-situ treatment with pump and treat approaches)
- In-situ remediation of contaminated soil and groundwater—often referred to in this context as source removal
- Non-engineered/institutional controls such as zoning, deed restrictions or resident relocation

Numerous other EPA resources are available to provide assistance with selecting technologies and approaches associated with source control. See, for example:

- http://www.clu-in.org/remed1.cfm
- http://www.epa.gov/superfund/policy/ic/index.htm
- http://www.brownfieldstsc.org/pdfs/Roadmap.pdf
- Various state guidance documents are also discussed in this paper and are listed in the reference section.

This document, however, focuses on the engineered controls implemented at the affected structure(s), which can be considered interim remedial measures. The mitigation approaches dealt with in this paper are primarily engineered "direct" mitigation strategies for vapor intrusion such as sealing of entry routes, sub-slab venting, or installation of membrane barriers. A formal definition of engineering controls, as provided in American Society for Testing and Materials (ASTM) E2435-05 (ASTM, 2005), is as follows: "Physical modifications to a site or facility to reduce or eliminate the potential for exposure to chemicals of concern."

[1] Though the revised guidance has not been released, recent presentations by EPA staff provide an overview of possible changes—see for example http://iavi.rti.org/attachments/WorkshopsAndConferences/0910_-_Schuver.pdf

Other Sources of Indoor Air Pollutants:

In addition to vapor intrusion, there are many other causes of poor indoor air quality (e.g., exposure of building occupants to contaminated well water/shower water), and other pollutant sources in the indoor environment. Readers interested in a more general view of indoor air quality can refer to EPA's indoor air website (http://www.epa.gov/iaq/index.html), which among other resources includes:

- A general overview of indoor air issues http://www.epa.gov/iaq/pubs/insidest.html
- Specific resources for indoor air problems in homes http://www.epa.gov/iaq/homes/
- Resources for large buildings/offices http://www.epa.gov/iaq/largebldgs/
- Resources for schools http://www.epa.gov/iaq/schools/

Radon and other Inorganic Species

Although radon mitigation theory and methods form a substantial and relevant foundation for the mitigation techniques and approaches discussed here, the intent of this paper is to discuss mitigation as applied to vapor intrusion of toxic VOCs. Mitigation approaches specific to inorganic species such as radon are covered by other resources (e.g., http://www.epa.gov/radon/).

2.2 Overview of Contaminant Entry into Structures and Mitigation

The majority of vapor intrusion cases occur when contaminants from either the soil or groundwater enter the soil gas at the water table or in the vadose (unsaturated) zone. The contaminated soil gas then migrates under the influences of advective flow or diffusion until they escape into the atmosphere or enter the zone of influence of a building. The term "advective flow" here refers to bulk flow driven by pressure or density differences.

One additional mode of entry occurs when contaminated groundwater itself enters the building. Entry of groundwater may occur in sumps or in flooded basements, where contaminants dissolved in the water may partition directly to the indoor air. This situation is believed to account for only a small fraction of the buildings with indoor air contaminated by chemicals originating in the soil but it is a very significant risk pathway when it does occur.

Volatile chemicals can enter the vapor phase via partitioning across the groundwater/soil gas interface (a process which at equilibrium can be described by Henry's law). Volatile species can also enter soil gas via volatilization from a free phase contaminant or adsorbed contaminant. Contaminants may undergo transformation in the subsurface, and the flux of contaminants may vary seasonally or otherwise due to changes in soil moisture, height of the water table, barometric pressure, and other factors. More quantitative discussion of these processes is provided in the users guide to the Johnson & Ettinger (J-E) model (Environmental Quality Management, 2004). Once in soil gas, deep in the soil and absent any natural or anthropogenic preferential flow conditions, diffusion dominates the soil vapor transport process; but near the building, advective flow is the dominant mechanism. The building's zone of influence arises from two primary effects:

1. The building constitutes a barrier to the free upward migration of the contaminants so they tend to accumulate under the building.
2. The building interacts with the soil through pressure differences that are induced between the interior of the building and the soil.

A basic conceptual model of subsurface contaminant movement into the sub-slab space involves the migration of volatile contaminants upward from a contaminated soil or groundwater source, through soils, to the engineered fill material which may underlie a building slab. In this sub-slab space, the distribution of contaminants is dependent on a number of factors, including the distance from and geometry of the source area, geological influences on vapor migration, and footing design. Sub-slab vapors may also follow preferential pathways such as utility corridors instead of collecting uniformly under the slab or above the source (NJDEP, 2005). Sub-slab vapors can then migrate into the overlying structure. Vapor migration into residences is generally thought to be at its maximum during the cold season, when there is a significant difference in temperature between ambient and indoors. An exception to this generalization may occur in karst terrains where radon has been observed to have higher indoor values during the summer months, because air flows in nearby underground caves can control contaminants' flow in the sub-slab region. The term "karst" refers to an irregular limestone region with sinkholes, caves and underground drainages formed by dissolution and solution processes. For houses built over caves at large distances from the entrance, air tends to flow through the cave system away from the house in the winter and toward the house in the summer. The pressures in these cave systems can be coupled to the house pressure (Gammage 1992).

When the pressure in the lowest portion of the building (i.e., basement, crawlspace or ground floor) is lower than the pressure in the soil below the building soil gas advectively flows into the building through cracks or openings. This negative pressure in the building is often due to the stack effect (buoyancy of warmer indoor air), barometric pressure changes or the interaction of the building with winds. This advective flow of contaminated soil gas is the primary mechanism by which soil vapor intrudes into buildings. It is much more important than direct diffusion through pores.

Only after advective flow through macroscale cracks has been substantially reduced (by reducing driving forces and closing entry routes) does diffusion through concrete slab pores become the dominant entry mechanism. Typically this situation occurs only in buildings in which the foundation has been specifically engineered to prevent entry of soil gases through cracks. Diffusion constitutes a significant risk pathway only if the concentration in the sub-slab soil gas is very high or the slab is unusually thin and porous. Unparged cinder block walls are, however, a separate case. Cinder blocks are intentionally designed to be lighter than concrete blocks and are more porous. Advective flow through cinder block walls is therefore likely.

The stack effect is a process that induces a negative pressure in the interior of the building as warm air rises and escapes through the top of the building. In turn this process draws replacement air in through the openings in the lower portion of the building; some of these openings will draw in soil gas. The stack effect is less strong in the summer time in buildings with a cooling system running. Although, this simplified view of the stack effect would suggest that the flow would reverse directions in the summer, empirical observations indicate that the driving forces across the slab still are in the direction of vapor intrusion during the summer, at least on average over 24 hours. The phenomenon of summertime soil gas entry is probably aided by the fact that the temperature in the sub-slab remains lower than the indoor air temperature during summer. This phenomenon is further supported by observations that warm climates such as Florida continue to have radon problems, though perhaps reduced, during the summer. (The stack effect is explained more fully at http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd104_e.html).

Negative pressures in a building can also be enhanced by mechanical systems such as heating and cooling systems, exhaust fans (including those built into stoves or grills), clothes dryers, central vacuums and combustion devices, especially fireplaces. The effect of clothes dryers, central vacuums, etc., only occurs when they exhaust outside. Since bathroom, kitchen, or utility room ventilation fans remove large volumes of air from those rooms, the rooms may depressurize if the doors are shut. This depressurization could cause at least brief periods of high vapor intrusion if the kitchen, bath, or utility room is on the lowest floor (in contact with the soil). The exposure period in these cases can be short. "Whole house" or building exhaust fans, if operated for a long period of time, can cause significant depressurization in whole buildings, especially if there is no system providing an inflow of outside air.

In order to have a potential vapor intrusion problem, there must be:

- Contaminants in the soil gas
- Entry routes for soil gas to enter the building
- Driving forces (pressure gradients or diffusion gradients) to draw the contaminants into the building. (Geyer, 2006)

A method for removing any one of these three conditions would constitute mitigation. Removal of the source is the definitive long-term solution. However, it should be noted that many contaminant removal (remediation) technologies, or passive methods such as natural attenuation, might require years or even decades [see section 6.1.2 of ASTM (2005)]. Moreover, there may be natural sources of contaminants such as radon or methane that cannot be effectively removed. Consequently, it is necessary to utilize one or a combination of the other two conditions to create intermediate mitigation methods to protect the public health.

The primary options are to:

- Prevent entry of the contaminants into the building or
- Remove the contaminants after they have entered

2.2.1 A Simplified Conceptual Model of Vapor Entry to Structures

As a conceptual model for understanding the entry and removal of soil gas contaminants in a building, the building can be viewed as a single zone enclosed by a continuous shell that may have small openings through which air can flow in or out. The lower portion of this zone is in contact with or is somewhat sunken into the soil. For simplicity, assume the contaminant of concern (COC) is initially located only in the soil gas and that it does not change with time. Suppose the driving forces for entry are dominated by the stack effect which draws soil gas into the building. If we assume the contaminants do not adsorb on surfaces significantly and do not react chemically, then a steady indoor concentration exists when the entry rate matches the removal rate. For this simplified model, the important building features are the ones that influence the soil gas entry rate and the air exchange rate.

Suppose for a moment that the only openings in the building were located at the top and near the bottom. According to the known stack effect, the pressure near the top is slightly positive causing air to flow out through the upper openings, while the pressure near the bottom is equally negative causing air and soil gas to enter through the lower openings. At about mid height, the pressure would be zero (neutral pressure plane) suggesting that no air would enter or leave at this location even if an opening were present (caution: large openings in the shell can distort the local pressure distribution in that part of the zone). Under the scenario of top and bottom openings, when the outdoor temperature drops the magnitude of the positive pressure at the top and the negative pressure at the bottom would both increase, resulting in an increased entry rate at the bottom and a corresponding increased flow out at the top.

For this simple one zone case, mass conservation requires the contaminant entry rate to be equal to the removal rate ($Q_s C_s = Q_i C_i$) where Q_s is the entry flow rate of soil gas, C_s is the concentration of the contaminant in the soil gas, Q_i is the flow rate of indoor air leaving (exfiltration) through openings above the neutral pressure plane of the building, and C_i is the indoor concentration of the contaminant.

When all the entry routes are located at the bottom of the structure, approximately the same pressure differential drives the entry of ambient air and soil gas. Consequently, the ratio of Q_s and Q_a (entry flow rate of ambient air) would be expected to remain nearly constant as the outdoor temperature decreases. Therefore, the indoor concentration would not change very much as the air exchange rate increases with falling temperature. This phenomenon occurs because the soil gas entry rate increases in proportion to the increase in the air exchange rate.

Since the scenario of openings only at the top and bottom is often not realized, the indoor concentration of soil gas contaminants will not always be independent of the air exchange rate. In fact, opening a window below the neutral pressure plane will usually result in an increased air exchange rate without proportionately increasing the entry rate of soil gas. Similarly, it is possible to open a window above the neutral pressure plane and increase the indoor concentration. The implication is that if one opens a window on an upper floor, a window on the lowest floor should also be opened to avoid pulling more soil gas into the building.

According to this simplified conceptual model, the important building features are the location and size of openings which can influence the magnitude and distributions of the pressure differentials. The limitations of this model become apparent when larger and more complex buildings that cannot be represented by a single zone are considered. Multiple zones require descriptions of the interactions and exchanges among the zones. Detailed discussion of such complex models is beyond the scope of this document.

From a mitigation perspective, it is usually not necessary to model the details of a very complex building. The important observation is that the contaminant comes from the soil gas, which enters the portion of the building that is in contact with the soil. If contaminant entry can be denied in the lowest part of the building, it may not be necessary to deal with the rest of the building.

For tall buildings, however, there are some potentially important observations:

- Tall buildings give rise to strong stack effects.
- Isolating individual stories of a tall building by sealing the floors reduces the stack effect.
- Floors act as dampers that reduce the stack effect pressures by preventing upward flows.
- Elevator sumps may be required by code to have drains at the bottom, not connected to sewers. These

drains should be equipped with one-way valves or traps below the slab to prevent soil gas entry.

2.2.2 Prevention of Contaminant Entry into the Building

To prevent entry of the contaminants into the building, one must do one of the following:

- Eliminate the entry routes or
- Remove or reverse the driving forces (the negative pressure or diffusion gradients) that lead the contaminants into the building or provide a preferential pathway to divert contaminants away from the structure (section 2.2.3)

The two general approaches to eliminating the entry routes are to seal the individual routes or to create a barrier such as a membrane that isolates all the entry routes from the soil gas.

The pressure gradient that drives advective flow into the building can be neutralized or reversed by inducing a positive pressure in the building or a negative pressure in sub-slab soil gas. Installing a pipe under the slab that uses a fan to extract soil gas from under the slab and vent it to the atmosphere is the most common approach. Such a system is called a sub-slab ventilation system or sub-slab depressurization system. Sub-slab ventilation may also significantly reduce the diffusion gradient across the foundation.

2.2.3 Removal of Contaminants from Buildings

If the contaminants have not been kept out, then it is necessary to remove them. One approach to removing contaminants is by increasing ventilation. Natural ventilation may be accomplished by opening windows, doors, and vents. Forced or mechanical ventilation may be accomplished by using a fan to blow air into or out of the building. Exhausting air from the building will generally contribute to the negative pressure in the building resulting in increased infiltration of soil gas. Another option for removal may include collection on an adsorbing material (such as activated carbon) that can be either recycled or properly disposed. In a more rarely used approach some contaminants may be chemisorbed on treated sorbents that result in chemical breakdown of the contaminants.

2.3 Vapor Intrusion into Various Building Types

In order to understand the range of engineering controls available and how they may apply to a particular situation, it is essential to understand the range of building structures that are potentially subject to vapor intrusion. Structures can be classified on the basis of the following:

- Use
- Type of foundation/basement
- Type of heating/cooling/ventilation systems

Each of these characteristics can influence the choice of mitigation methodology and they are commonly documented on survey forms during vapor intrusion investigations. In some jurisdictions, this information also can be obtained from online property tax records.

2.3.1 Classification by Use

Structures can be classified by use:

- Residential (subdivided into single family or multi-family)
- Commercial/multi-use
- Industrial
- Educational/governmental
- Religious/community

These different uses are characterized by different typical periods of occupation (exposure durations). Residential, commercial, and industrial buildings also differ in the factors that influence the dilution of intruding vapors [characterized by their air exchange rate (AER)]. The AER is the rate at which outside air replaces indoor air in a building. These and other terms common in discussions of indoor air quality are described more fully in EPA's Indoor Air Glossary (http://www.epa.gov/iedweb000/glossary.html). If the use of a building changes after a mitigation system is installed, the exposure scenarios and thus the mitigation objective may need to be reevaluated.

2.3.2 Classification by Foundation Type

Structures can be classified by foundation type:

- Basements (with concrete slabs or dirt floors)
- Slab on grade
- Slab below grade

- Foundation/crawlspace (the foundation may be wood, stone, brick or block masonry, poured in place concrete or precast concrete panels)
- Footings/piers
- Mobile home

Slabs, whether on grade or below are typically not simple rectangular solids. Slabs are usually supported under the load bearing walls either by a block foundation or by a thicker section of a monolithically poured slab.

Figure 1 shows some of the main entry routes of vapor intrusion (advective flow). For all structural types, utility penetrations through floors and basement walls are a key route of entry—these are shown schematically in Figure 2. The most common routes of vapor intrusion include:

- Seams between construction materials (including expansion and other joints)
- Utility penetrations and sumps
- Elevator shafts
- Cracks, etc.

A fairly extensive diagram of potential routes of entry is also provided as Figure 2-2 of EPA (1993a). (http://www.clu-in.org/conf/tio/vapor_021203/pb94110517.pdf)

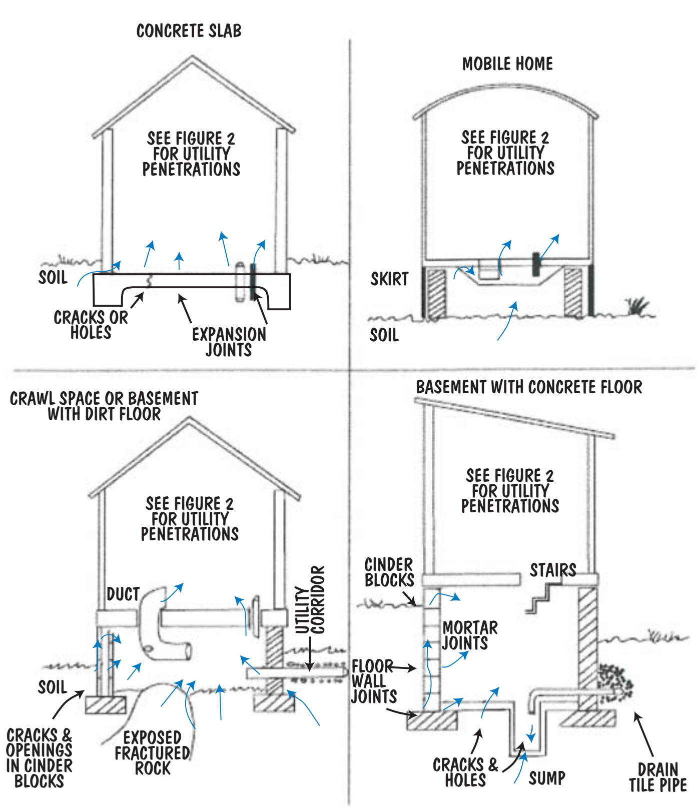
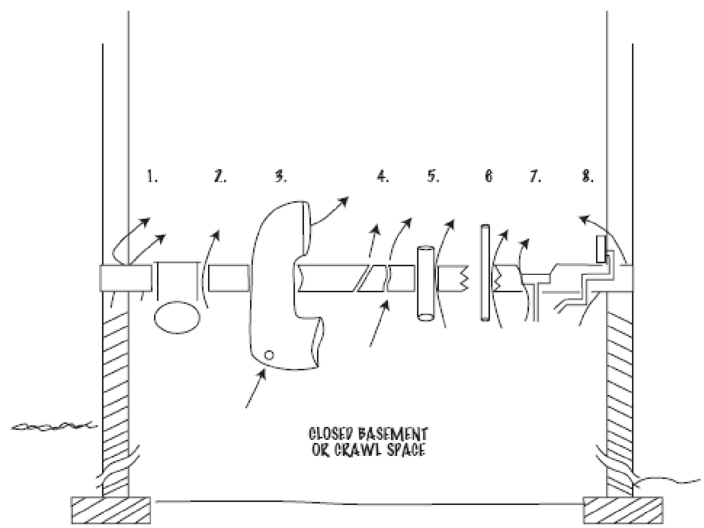


Figure 1. Vapor intrusion potential in various residential structural types.

Poured concrete walls are generally less permeable than those constructed with cinder blocks. Cinder block walls can thus be a significant entry route.

2.3.3 Classification by Ventilation

Structures can also be classified based on their **heating/cooling/ventilation methods.** While a detailed discussion of systems is not included here, it is important to assess how the system or combination of systems controls the airflow in the structure and thus may influence vapor intrusion. Some systems will increase pressure, while others will decrease pressure inside the structure. If the net infiltration increases over the net exfiltration, the resulting pressure change will be positive. If the exfiltration increases more than infiltration, the pressure change will be negative. In some cases information on heating, ventilation and air conditioning (HVAC) design and operation may be available from a previous Test and Balance report or energy audit.



Legend Figure 2

1. Structural openings
2. HVAC vents
3. HVAC return duct (with hole)
4. Gaps and cracks
5. Sewer pipe
6. Water pipe (note large cutout, e.g. for bath and shower drains)
7. Drain or sump
8. Electrical, phone or fiber optic line

Figure 2. Vapor intrusion pathways through utility penetrations and structural openings in floors and walls.

2.4 Quality Assurance Considerations

Achievement of customer and stakeholder objectives in vapor intrusion mitigation requires that a quality system be established and followed both in:

- Measurement activities (air concentrations and engineering parameters such as pressures)
- Mitigation technology selection, site specific engineering design and construction.

Quality assurance considerations for measurement activities, especially the verification of mitigation system performance are covered in sections 5.1 and 5.2 of this document and in EPA 2002b.

It is essential that quality considerations be embedded throughout the steps of:

- Organizing a project team with appropriate qualifications and experience
- Developing project team communication strategies and document controls
- Establishing requirements and objectives for the needed engineered systems
- Conducting feasibility studies to select technologies
- System design, including design inputs and design document review
- System construction—including procurement, inspection, verification testing and control
- Building system performance testing
- Operation and monitoring—including development of procedures, system startup, inspection, and testing

Although these topics are not treated at length in this engineering issue paper, readers are urged to consult:

- Guidance on Quality Assurance for Environmental Technology Design, Construction, and Operation http://www.epa.gov/QUALITY/qs-docs/g11-final-05.pdf
- Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA http://www.epa.gov/superfund/policy/remedy/pdfs/540g-89004-s.pdf
- Quality Control and Safety During Construction http://pmbook.ce.cmu.edu/13_Quality_Control_and_Safety_During_Construction.html
- Integrated Design Process http://www.sbc.nrcan.gc.ca/buildings/pdfs/IDP_overview.pdf

As will be discussed later in this document, many specific quality assurance documents developed for radon are also useful for other types of vapor intrusion mitigation

- "Model Standards and Techniques for Control of Radon in New Residential Buildings" U.S. Environmental Protection Agency, Air and Radiation (6604-J) EPA 402-R-94-009, March 1994
- ASTM E2121 Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings
- Radon Prevention in the Design and Construction of Schools and Other Large Buildings Third Printing with Addendum, June 1994 http://www.epa.gov/ORD/NRMRL/pubs/625r92016/625r92016.pdf
- Radon Reduction Techniques for Existing Detached Houses: Technical Guidance (Third Edition) for Active Soil Depressurization Systems [EPA 625/R-93-011, October 1993]

3 AVAILABLE ENGINEERED CONTROL MEASURES

Vapor intrusion can be mitigated either during construction or as a retrofit on an existing structure. Strategies for mitigating vapor intrusion include both active and passive techniques, both of which require careful engineering design.

Decisions to mitigate are made primarily on the basis of a demonstrated potential for vapors migrating from subsurface to yield an unacceptable risk. Mitigation may also be undertaken as a proactive measure to avoid a costly characterization study. Remedial actions may also be based in part on site-specific factors that influence decisions on how to manage a threat or the speed with which a responsible party responds to elevated contaminant levels (building construction, building occupants, vapor concentrations, projected time for the remediation of contamination, etc.) [Colorado Department of Public Health and Environment (CDPHE) 2004]. Such decisions will take into account whether implementation is based on single sample results or multiple samples collected over a period of time to account for seasonal variations.

Figure 3 provides a generalized flow chart of the different steps required for decision-making and selection of an appropriate vapor intrusion mitigation technology. This figure begins after a vapor intrusion investigation and risk assessment have been performed and a decision to mitigate has been made.

In most cases, active mitigation is based on achieving a negative pressure gradient underneath a structure, which more than compensates for the house depressurization generated by the environment (the primary driving force for vapor intrusion). Alternatively, when a relatively small reduction (less than a factor 2) is sufficient, active measures may be based on removing or diluting vapors after they have entered the building (Babyak and Welt, 2006). This approach requires a removal rate that is greater than the contaminant entry rate.

Active mitigation strategies, which typically require some ongoing consumption of energy, include the following (ITRC, 2003):

- Sub-slab depressurization systems that either reverse the direction of air flow or dilute the contaminants with ambient air
- Drain-tile depressurization
- Block wall depressurization
- Sub-membrane depressurization
- Site remediation technologies such as soil vapor extraction
- Indoor air purifiers or adsorption systems such as carbon filtration
- Heat recovery ventilation technology
- Adjustments to building HVAC systems that increase AER or produce high, positive, sustained indoor/outdoor pressure differences

Passive mitigation approaches include:

- Passive sub-slab venting, a technology that relies on convective flow (further discussed below)
- Sealing the building envelope (outer shell) or installing vapor barriers
- Modification of the building foundation
- Measures to increase natural ventilation such as opening windows, doors, and vents
- Selective placement of buildings on the site to avoid contact with the vapors
- Building on stilts, also known as pier construction
- The selective placement of occupancy spaces within the building away from spaces directly affected by vapor intrusion
- Use of construction materials inherently resistant to vapor intrusion (i.e., passive barriers)
- Specialized building designs to minimize pressure differentials across the building shell. For example, the structure can be designed to minimize the stack effect. Building orientation with regard to prevailing winds can also have an impact (Geyer, 2006). In addition, the building can be designed with additional windows or vents for ventilation of non-living space with low exposures on the lowest level, e.g., a garage.

Experience (mainly gathered from radon and methane vapor intrusion work) shows that active systems are needed if a large decrease in the amount of vapor intrusion is required (EPA 1993b, Section 1.4). Passive sub-slab systems show a performance range that varies from 30–90 percent efficient (EPA 1993b). These performance results were mostly obtained from short term

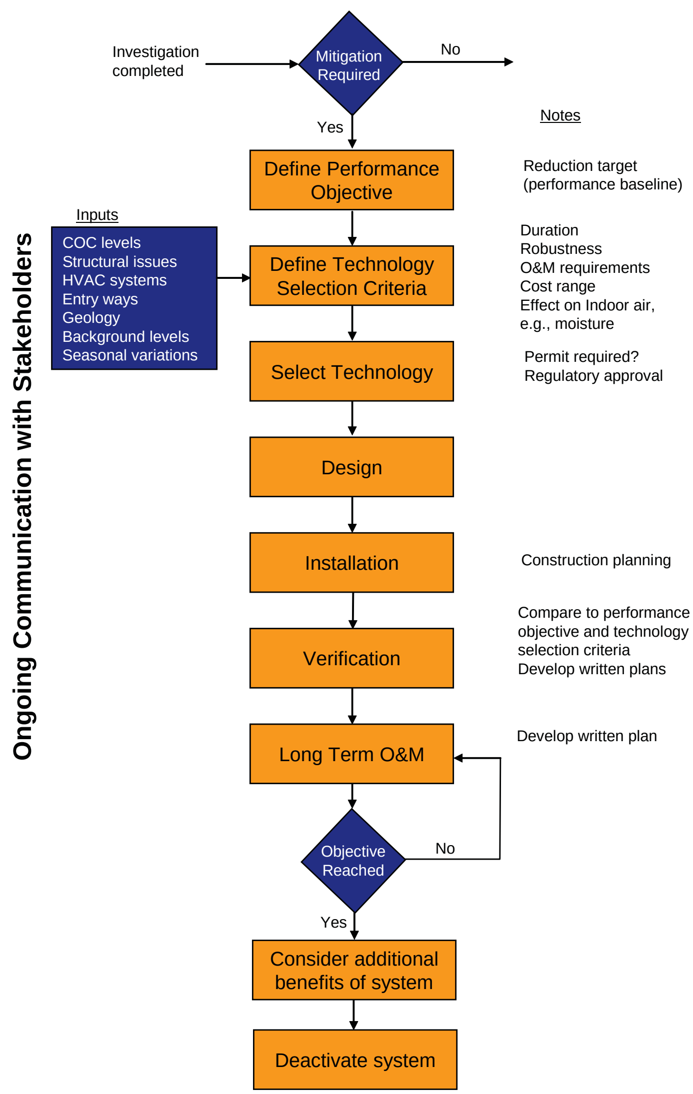


Figure 3. Flow chart for decision-making and technology selection after a vapor intrusion assessment determines that mitigation is required.

monitoring. Few passive systems have been adequately monitored for long periods of time. In many cases, the performance of passive depressurization systems decreases substantially during warm seasons (NAHB Research Center, 1996).

If passive techniques are insufficient to limit risk or hazard, more active techniques may be used to prevent the entry of vapor contaminants into a building.

As applied to the development or redevelopment of contaminated properties (e.g., a brownfields redevelopment project), mitigation strategies should be considered early in the planning phase and incorporated into the engineering design to eliminate or minimize vapor intrusion. These up-front capital costs are often as much as 60 percent less than the costs for installing more intrusive mitigation systems as retrofits.

Table 1 (used with permission from Babyak and Welt, 2006) includes an overview of engineering controls, as well as comments and cost data for these techniques.

3.1 Active and Passive Sub-slab Ventilation

The most commonly accepted mitigation techniques use active or passive sub-slab depressurization (SSD) systems developed for use in radon mitigation (Babyak and Welt, 2006). Radon mitigation systems are typically designed to achieve a sub-slab pressure field that more than adequately compensates for the depressurization of the building. Generally, the average range of soil/building depressurization is on the order of 4-10 Pa. Thus, a mitigation system that compensates for a minimum of 4-10 Pa everywhere under the slab should adequately mitigate vapor intrusion. The actual depressurization necessary to achieve the desired risk level reduction in vapor intrusion may vary and performance should also be based on demonstration of the requisite reduction in risk level. If the soil permeability of the sub-slab region is high so that it is not possible or economical to achieve or maintain a pressure field extension of 4-10 Pa, then system design should be based on achieving and maintaining ventilation airflow under the building sufficient to capture radon or VOCs in spite of the building depressurization. In this scenario, the sub-slab concentration must decrease substantially after the mitigation system has been operating for an extended period of time (several days). For surrounding lower permeability regions, significant time may be needed to dilute local concentrations.

The hardware used in sub-slab ventilation (SSV) systems and sub-slab depressurization (SSD) systems is similar. The two names describe the different mechanisms through which the system can be effective in keeping soil gas contaminants out of the building. When the surrounding soil has a relatively high permeability, the fan pulls large quantities of air (largely from the atmosphere) down through the soil thus diluting the contaminant in the sub-slab region resulting in reduced entry into the building. This mechanism predominates in a sub-slab ventilation system. It is important to ensure that openings in the slab and foundation are adequately sealed to prevent large quantities of conditioned indoor air being pulled into the mitigation system. Sealing as part of SSD system installation is discussed in EPA 1993b, section 4.7 and in NYSDOH, 2006, section 4.3.1.

When the soil is much less permeable, less air flows and the fan generates a larger negative pressure in the sub-slab region (thus sub-slab depressurization occurs). The result is a larger negative pressure gradient across the slab. The system works because the negative pressure gradient ensures that the flow is in the direction from indoors to the soil and dilution of sub-slab gases is less important in this SSD case. In extreme cases of low permeability and low flows, it may be necessary to specify a special blower to ensure that adequate pressure gradients are generated. Engineering aspects of sub-slab systems will be addressed later in this document.

The following factors should be considered when designing SSD/SSV systems:

Spacing of Collection Points: Active system collection points (sometimes referred to as “suction points”) and manifold piping are installed immediately beneath or adjacent to the slab. The number and spacing of collection points (EPA, 1993b; Fowler, C.S. et. al., 1990) should be based upon diagnostic testing (e.g., pilot testing and communication testing) reflecting the properties of the soil and fill underneath the building. The lengths and diameters of all piping should be appropriate for the design capacity of the system. Horizontal manifolds are usually not required when an adequate layer of clean aggregate is present. Building codes in most areas now require such layers of sub-slab aggregate but they may not be present in existing structures.

Selection of Sub-slab Collection Points or Manifold Pipe Layouts: Collection points or a sub-slab manifold piping network are used to ensure good coverage under

Table 1. Overview of Mitigation Methods with Cost Data (adapted from Babyak and Welt, 2006)

Remedy	Description	Comments/ Regulatory Acceptance	Cost
Ventilation Technologies—General Characteristics		Need to maintain and always keep in place	
HVAC adjustment to take in more outside air and pressurize building	Building design for slightly positive pressure compared to outdoor.	Established for large structures; less common for residential. Need to maintain and always run HVAC system fan. About one third of the states currently use this method as a mitigation measure.	Capital: $ 0 Annual Operation and Maintenance (O&M): $200–$750. Note: This estimate assumes the current HVAC system is capable of continuously supplying the necessary pressure, and that only periodic checks/adjustments will be required.
Enhanced ventilation without pressurization	Increased indoor ventilation (AER). Increase of ventilation must be done without reducing the pressure of the interior space. More negative indoor pressures would be likely to actually increase vapor intrusion!	Unlikely for residential structures because of energy cost impact. May be acceptable in unconditioned areas (e.g., garages). Need to maintain and always run system. About one third of the states currently use this method as a mitigation measure.	Capital: $300–$1,000 (capital likely to be higher, i.e. $3,000–$5,000 if heat recovery is implemented). Annual O&M: $100–$500. Note: This estimate assumes a few(e.g., 2–4) new vents between the space to be treated and ambient air and/or supply fans will be installed.
Passive measures—general characteristics	Need to maintain and always keep in place. Installation is appropriate only when residual VOCs in soil gas are unlikely to contribute to unacceptable air impacts (e.g., soil vapor concentrations are below levels of health concerns). 30–90% reduction in vapor intrusion is possible. Subject to seasonal variations in effectiveness.		
Sealing	Seal cracks and other openings in the foundation.	Residential and commercial buildings. Need to maintain. Hard to find and seal all openings. About one third of the states allow sealing of the building as a control measure to be used alone.	Capital: $2.00–$3.00 per linear ft. Annual O&M: $200–$500. Note: This estimate assumes an existing slab in fair condition (i.e., cracking is not excessive).
Vapor barrier—geomembrane	Impermeable geomembrane placed beneath building.	Residential and commercial buildings only in new construction—not feasible as a retrofit. Feasibility depends on foundation design, typically combined with a sub foundation vent system. Maintenance is easy. Less environmental concerns. Can use HDPE (40–60 mil), LDPE, or VDPE (30 mil).	Capital: $0.75–$1.50 per sq ft. Annual O&M: N/A. Note: This estimate assumes appropriate bedding material will be provided.

Table 1. Overview of Mitigation Methods with Cost Data (adapted from Babyak and Welt, 2006) (continued)

Remedy	Description	Comments/ Regulatory Acceptance	Cost
Vapor barrier—spray-on (i.e., Liquid Boot, epoxy paint).	Placement of a spray-applied vapor membrane. The membrane may be a rubberized asphalt emulsion or an epoxy (method of sealing all cracks and potential vapor intrusion points).	Residential and commercial buildings. If this is sprayed indoors VOC emission (off-gassing) is high during application—Level B PPE required[1] and close business until indoor air quality has returned to acceptable levels. Installation may take a few days (depends on thickness required, building conditions, weather conditions, etc.) since each layer needs to off-gas before the next one is applied. Spray-on membrane may be difficult to maintain as it may flake or become damaged; it is also hard to repair (patch).	Capital: $5.00–$7.00 per sq ft. Annual Operation and Maintenance (O&M): $500–$2,000. Note: This estimate assumes multiple layers (applications) will be required to achieve adequate thickness.
Passive sub-slab ventilation [vapor barrier (i.e., spray-on or geomembrane) and passive gas venting system].	Placement of a vapor barrier and an additional venting system. System consists of a vent pipe (or a series of vent pipes) installed through the slab—relies on convective flow of warmed air upward in the vent pipe to draw air from beneath the slab.	Residential and commercial buildings. Type of sub grade: permeable.	Capital: $500–$3,000, plus vapor barrier costs (see above). Annual O&M: N/A. Note: This estimate assumes that vertical vent pipes will be adequate, and a network of horizontal collection pipes will not be needed beneath the membrane.
Passive crawlspace ventilation [vapor barrier (i.e., spray-on or geomembrane) and passive gas venting system].	Placement of a vapor barrier with an additional venting system beneath. Venting system consists of a series of collection pipes installed beneath building—relies on convective flow of warmed air upward in the vent to draw air from beneath the slab.	Residential and commercial buildings. Note: Geomembrane barrier is best. Type of sub grade: permeable. Need to maintain and always keep in place.	Capital: $500–$3,000, plus vapor barrier costs (see above). Annual O&M: N/A. Note: This estimate assumes that vertical vent pipes will be adequate, and a network of horizontal collection pipes will not be needed beneath the membrane. If a network of horizontal collection pipes is needed, the installation cost would be significant and other options should be considered.
Active measures—general characteristics		Need to maintain and run constantly. Requires significant stakeholder communication in residential buildings due to long-term maintenance requirements.	
Active sub-slab suction [active gas venting system with or without vapor barrier (i.e., spray-on or geomembrane)].	Placement of additional venting system consisting of a vent pipe (or a series of vent pipes) installed through the slab and connected to a vacuum pump to extract the vapors from beneath the slab. May be installed in conjunction with a vapor barrier.	Need to maintain and always keep in place. Requires on-going monitoring and maintenance of mitigation system. Up to 99.5% reduction in vapor intrusion is possible. About 40% of the States currently use this technique to control vapor intrusion; this is the most widely used and accepted approach (from Radon Industry).	Capital: $1,500–$5,000, plus vapor barrier costs (see above). Annual O&M: $50–$400. Note: This estimate assumes that vertical vent pipes will be adequate, and a network of horizontal collection pipes will not be needed beneath the membrane.

Table 1. Overview of Mitigation Methods with Cost Data (adapted from Babyak and Welt, 2006) (continued)

Remedy	Description	Comments/ Regulatory Acceptance	Cost
Crawlspace depressurization [active gas venting system with or without a vapor barrier (i.e., spray-on or geomembrane)].	Placement of an additional venting system which uses fan-powered vent system to draw air out of crawlspace. May be installed in conjunction with a vapor barrier.	Commercial and residential Buildings. Need to maintain and always keep in place. Requires on-going monitoring and maintenance of mitigation system. Up to 99.5% reduction in vapor intrusion is possible. About one quarter of the States use depressurization. Most states have not yet addressed the issue.	Capital: $1,000–$4,000, plus vapor barrier costs (see above). Annual O&M: $50–$400. Note: This estimate assumes one fan will generate adequate suction for multiple vent points.
Sub-membrane depressurization	Fan-powered vent draws air from beneath a soil gas retarder membrane (laid on the crawlspace floor).	Residential and commercial buildings. Need to maintain and run constantly. About one quarter of the states use depressurization. Most have not yet addressed the issue.	Capital: $1,500–$5,000, plus vapor barrier costs (see above). Annual O&M: $50–$400. Note: This estimate assumes that vertical vent pipes will be adequate, and a network of horizontal collection pipes will not be needed beneath the membrane.
Block wall depressurization	Depressurizes the void network within a block wall foundation by drawing air from inside the wall and venting it to the outside.	Residential and commercial buildings. Need to maintain and run constantly. Requires sealing of major openings.	Capital: $1,000–$5,000. Annual O&M: $50–$200. Note: This estimate assumes the structure currently has a block wall foundation.

General Cost Estimate Notes:

1. All costs include labor, equipment, and materials, unless otherwise noted.
2. Costs do not include treatment of gases unless specifically noted.
3. Unit costs are in 2004 dollars and are estimated from standard estimating guides, vendors, and professional judgment and experience from other projects.
4. Costs are based on a building footprint up to approximately 4,000 square feet.
5. Cost estimates are for the purpose of comparing relative costs of these options against each other and do not represent actual design or construction cost estimates. A design/ construction cost estimate can be prepared when additional site-specific details are available.
6. These costs do not include: coordination, permitting, procurement, observation/oversight, reporting, air monitoring/laboratory analysis, or as-built drawings. Costs may require future revision based on design, contractor quotes, required permits and other factors.
7. The range of costs presented in this table is based on a review of literature (see Babyak 2006) and based on discussions with subcontractors and vendors).
8. The true installation and operation and maintenance costs will depend on the site specific conditions and use.

the slab. Collection points often involve voids in the soil, sometimes called suction pits, to improve the pressure field extension under the slab. Mainfold installations will be required for unusually large buildings or when the building does not already have an effective air movement pathway below the slab (i.e., aggregate, sand, etc.).

- *Multiple sub-slab collection points connected through a vertically configured system of riser pipes (most common).* In cases where multiple collection points are used, vertical riser pipes connect the suction points in the floor of the building. These riser pipes rise vertically to the ceiling where piping may be most efficiently consolidated into a single manifold pipe and run to a common location for exhaust.

- *Horizontal Sub-slab Piping Network (less common).* In this case a sub-slab network, of horizontal piping is installed under and/or around the perimeter of buildings. Such systems are typically associated with new construction as it is usually uneconomical to install horizontal pipes in trenches under existing buildings. In some cases, horizontal drilling techniques may be used to install piping under existing buildings.

With both vertical and horizontal multiple collection point systems, some designers have incorporated pressure regulating valves to allow the suction at the various points to be controlled (Dilorenzo 2007).

In all cases, care should be taken on installation of the SSD/SSV system so that damage to building footings and utility corridors is avoided. Also, deviations in pressure fields or air flow patterns arising from the presence of footings and utility corridors must be taken into consideration. The need for drainage or de-watering improvements to prevent soil moisture condensate blockage of any portion of the collection piping should be evaluated and suitable improvements contemplated, as necessary, to ensure the proper operation of the collection pipe system. There should be no low points for water to collect in the lines and the pipes should be sloped to allow water to drain to the soil.

Design of System Vent Risers: Depending upon the size of the building and the number of system fans/pumps needed, system piping will be consolidated into one or more vent risers that extend above the building. Vent risers should be equipped with a sampling port and fitted with a non-restricting rain guard to prevent precipitation and debris from entering the piping system. Mesh is also helpful to exclude debris, nesting birds and insects. Vent risers should be properly secured to the building for protection against damage and should terminate at a minimum of two feet above the roof of the structure and be a minimum of 10 feet away from any window or air intake into the building. As a general rule, the diameter of the vent riser should be appropriate for the capacity of the system; manifold piping is typically a minimum of 3 or 4 inches in diameter for residential buildings. A small fan or blower within the vent riser is used in active systems. If a fan or blower is warranted for the system, electrical power and controls must be provided.

Utility Conduit Seals: Seals should be retrofit at the termination of all utility conduits to reduce the potential for gas migration along the conduit to the interior of the building. These seals should be constructed of closed cell polyurethane foam, or other inert gas-impermeable material, extending a minimum of six conduit diameters or six inches, whichever is greater, into the conduit. Wye seals should not be used for main electrical feed lines. Design consideration should also be given to sump pump drains and seals, to ensure that they continue to provide drainage when needed without compromising the operation of the sub-slab depressurization system. Proper sealing of penetrations and entryways is especially important for a passive system because minor leaks in buildings can offset the small pressure differentials that passive systems rely on.

Additional design guidelines for SSD/SSV systems for VOCs are provided in (DiPersio and Fitzgerald, 1995), http://www.mass.gov/dep/cleanup/laws/ssd1e.pdf.

3.1.1 Active Systems: Active Venting or Sub-slab Depressurization (SSD) or Sub-slab Ventilation (SSV)

Active systems have been used successfully to mitigate the intrusion of radon into buildings and have also been successfully installed and operated in residential, commercial, and school buildings to control VOC vapor intrusion (Babyak and Welt, 2006). Active mitigation is the more effective approach for use in existing structures and/or where installation of a membrane system below the foundation is not feasible. Note that permits or authorizations from the local government may be required for venting systems that exhaust to atmosphere (DTSC, 2004).

Active systems, often referred to as active sub-slab ventilation (SSV) systems or sub-slab depressurization (SSD) systems, are the most common and usually the most reliable mitigation method. The terms SSD and SSV are frequently used interchangeably although the theory of operation differs as described above. The system most employed is the SSD.

EPA defines SSD technology as “a system designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a fan-powered vent drawing air from beneath the slab” (http://www.epa.gov/radon/pubs/newconst.html).

In practice, these systems operate by either:

- Generating a sub-slab pressure field that adequately compensates for the depressurization of the building (SSD), or
- Achieving adequate advective air flow under the building sufficient to dilute VOCs diffusing from soil or groundwater (SSV).

In rare cases where both SSD and SSV have been shown to be insufficiently effective, a third alternative is possible—sub-slab pressurization (SSP). SSP is normally used when the permeability of the soil is too high to allow a sufficient pressure to be generated for SSD but the fan does not pull enough flow for effective SSV. In these situations the fan can sometimes be reinstalled in the opposite orientation so that it blows into the sub-slab area creating a flow away from the slab. SSP has been shown to lead to improved performance in certain cases such as where homes are built on well-drained gravel soils or on highly fractured rock. SSP systems are not better than SSD systems in low-permeability soils even if there is a gravel layer beneath the slab (EPA 1993b). More information on these systems can be found in EPA 1993b and ITRC 2007.

A diagnostic criterion for adequate performance of an SSV system is more difficult to specify than such a criterion for SSD systems because the flows required for dilution are difficult to specify. Adequate negative pressures under the slab are a good indicator of SSD system effectiveness. Measurable negative pressures under the slab also can indicate SSV systems are working, but it is difficult to specify the pressure/rate of ventilation needed for an adequate working margin of safety. For this situation, indoor air sampling should be weighted heavily in the effectiveness evaluation.

As mentioned above, the most common approach to achieving depressurization beneath the slab is to install suction points through the floor slab into the crushed rock, drainage mat or pit underneath the slab. Ideally the slab will have been built on a gravel or sand layer or over a drainage mat (commercial drainage mat suppliers include enkadrain http://www.colbond-usa.com/, http://www.sgs-geotechnik.at/English/Products/Drainage_mats.htm, and http://www.versicell.com/drainage_cell.htm).

A negative pressure is applied at the suction points sufficient to achieve depressurization of approximately 4-10 Pa over the building footprint for SSD or the requisite airflow for SSV. Again, for depressurization-based systems, the actual depressurization necessary to achieve the desired level of risk reduction may vary and performance should be based, in part, on demonstration of the requisite reduction in risk level. This demonstration may best come from indoor contaminant concentration measurements, in the absence of significant indoor sources or from tracer gas attenuation tests. Excessive depressurization however can potentially lead to backdrafting (induced spillage of combustion gases) of combustion appliances, causing carbon monoxide exposure to occupants.

The number and location of suction points that are needed (as determined by visual inspections, diagnostic tests, and experience within similar building structures and contaminants) depends on how easily pressure or air can propagate in the crushed rock or soil under the slab, and on the strength of the VOC vapor source. With a clean aggregate layer one suction point is normally sufficient for 2,700 ft^2 of residential slab or 50,000 ft^2 of commercial slab (EPA 1993b). The results for commercial buildings are based on use of larger fans and larger diameter piping. This rule of thumb applies only when the slab was built at one time. A vent fan is connected to the suction pipe(s) drawing the VOC laden gas from within the soil pore spaces beneath the building and releasing it into the outdoor air, while simultaneously creating a negative pressure beneath the slab.

In the case of low flow systems (SSD), a sustained negative pressure at all points under the slab is needed for adequate performance of the system. As a practical matter SSD systems are normally designed to achieve a pressure differential of at least 0.02 inch of water (5 Pascal), during the worst case season, to provide an adequate safety factor for long-term variations. See Table 2 for pressure unit conversions.

Table 2. Reference Table of Pressure Unit Conversions

Multiply	By	To Obtain
Pascals	1	Newtons/m^2 (1 Newton is the force required to accelerate 1 kg at 1 m/$second^2$)
Atmospheres	101,325	Pascal
Pounds per square inch	6,894	Pascal
Bar	10^5	Pascal
Inches of Water	249	Pascal

Systems with only slightly negative pressure readings tend to exhibit rapid pressure variations swinging between negative and positive. Installations that cannot achieve the 5 Pa criterion for SSD recommended above but demonstrate adequate risk reductions, should be monitored more closely for long-term performance. For a reliable measurement, these fluctuations must be averaged over time periods of many minutes and sometimes over several hours, which requires a digital gauge with data-logging capabilities. The long-term average must remain negative over all seasons for the system to be effective. Performance of these systems should be further verified by another line of evidence such as an indoor air measurement.

Common fan locations include attics and the exterior of the building (Babyak and Welt, 2006). Fans should not be installed in basements, other potential living spaces, or any enclosed portion of the building that can potentially communicate with the living space, since a leak on the positive pressure side of the fan could introduce contaminants into the basement or living space (e.g., not in or under a living space). Fans (or in some cases blowers) should be selected to provide adequate flow and suction. However excessively large fans should not be selected because, though the capital cost increase might be small, excessively large fans could lead to increased energy cost in the long-term. There is a six page detailed discussion of fan selection for SSD in EPA 1993b section 4.4 which is also applicable for SSV. The most commonly used fans for SSD are 50–90 watt in-line, centrifugal fans. Ninety watt SSD fans are recommended for homes with good to marginal sub-slab communication. In cold climates a bypass for condensation drainage should be provided to prevent freezing and blockage of the fan. SSP fan selection is covered in EPA 1993b section 9.4.

Major design references for SSD/SSV technology include:

- ASTM E2121-03 "Standard Practice for Installing Radon Mitigation in Existing Low Rise Buildings" which is recommended by EPA http://www.epa.gov/docs/radon/pubs/mitstds.html and is focused on residential buildings.
- EPA 1993b for existing detached houses, EPA 1994b for schools, EPA 1994a for new residences, Fowler et. al., 1990 for low-permeability soils. Readers should also consider using the Florida (1995) guidance when working in areas with similar housing types and geologic conditions. Section one of the Florida guidance is for SSD in thickened edge monolithic slab poured into stem wall, slab capping stem wall, and slab-below-grade solid stem wall construction.

Engler (2006) provides design considerations for sub-slab depressurization and positive pressure systems to combat vapor intrusion. Both types of systems work with a fan and are therefore discussed together in this work. The paper includes a chart with data for pre-mitigation and post-mitigation indoor air concentrations of VOCs at thirty locations. In all but three cases, the VOC of concern was trichloroethene (TCE). Some conclusions can be drawn from this chart. For example, the effectiveness of the controls is highest for the highest pre-mitigation concentrations (around a factor of 100). The mitigation systems were either barely or not at all effective for the lowest pre-mitigation concentrations, which were approximately 0.2 $\mu g/m^3$ (0.04 ppb) TCE. The paper concludes that, based on the chart, vapor intrusion (VI) mitigations are highly effective when properly designed and installed (Engler, 2006).

Folkes and Kurz (2002) describe a case study of a vapor intrusion mitigation program in Denver, Colorado. Active soil depressurization systems have been installed in over 300 residential homes to control indoor air concentrations of 1,1-dichloroethene (DCE) resulting from migration of vapors from groundwater with elevated 1,1-DCE concentrations. Over three years of monitoring data have shown that these systems are capable of achieving the very substantial reductions in concentrations necessary to meet the concentration levels currently mandated by the state regulatory agency. Prior to installation of the system, 1,1-DCE indoor air concentrations ranged from below the reporting limit of 0.04 $\mu g/m^3$ to over 100 $\mu g/m^3$. Post-mitigation monitoring showed that in most cases, single suction-point systems with 90 watt fans were able to reduce 1,1-DCE concentrations by 2 to 3 orders of magnitude, well below the state-required standards. Approximately one quarter of the systems required minor adjustment or upgrading after initial installation in order to achieve the state standards (Folkes and Kurz, 2002; Folkes, 2003).

Another case study of a large vapor intrusion mitigation program is Hill Air Force Base (AFB) in Utah where 58 residential systems have been installed. Most (57) of the systems are sub-slab systems with one or two suction points. Additionally the program includes two crawl-space sub-membrane systems, one heat recovery ventilation system and four sump cover systems. As seen in Figure 4, the program has been successful in reducing concentrations significantly (Case, 2006; Elliot, 2005).

3.1.2 Variations of Sub-slab Depressurization (SSD)

Generally, creative variations of SSD depend on special construction features of the building. The variations that have been demonstrated to be successful are fully detailed and illustrated by Henschel (EPA 1993b). Some examples of variations are also found in (NYSDOH, 2005) and ASTM (2005):

Drain tile suction: Some houses have existing drain tiles or perforated pipe to direct water away from the foundation of the house. Suction on these tiles or pipes is often effective especially if the drain tile extends entirely around the building.

Sump-hole suction: If the building has a sump pump to remove unwanted water, the sump can be capped so that it can continue to drain water as well as serve as the location of a suction pipe. However, sumps connected to exterior drain tiles are not appropriate SSD points unless a one-way valve can be installed in the exterior drain line. If the sump is not used as the suction or extraction point, the associated wiring and piping should be sealed and an airtight cover should be installed, to enhance the performance of the SSD system. In systems with active dewatering, the potential for settlement over time should be considered in design of associated systems. Installation kits are readily available from mail order catalogs (i.e., Infiltech.com) to either cover the sump or convert it into a mitigation system. Nearly all materials needed for a complete SSD installation are available from manufacturer's web sites.

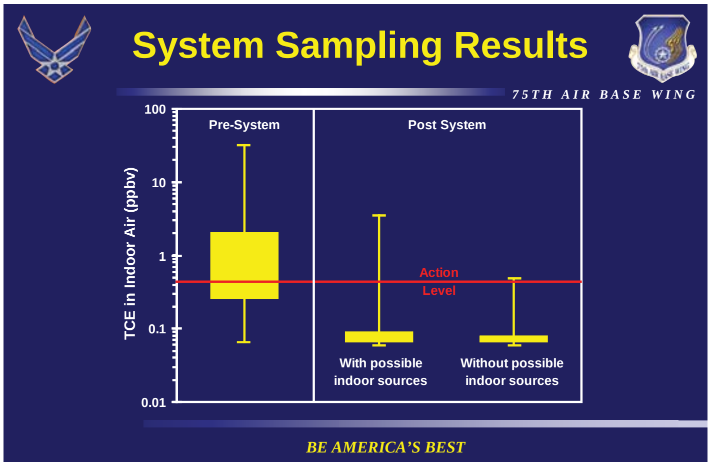


Figure 4. Results of the Hill AFB mitigation program.

Block wall suction: If the building has hollow block walls, especially if the outside surfaces are in contact with the soil and are not adequately purged, the usual sub-slab suction point may not adequately mitigate the wall cavities. In these cases the void network within the wall may be depressurized by drawing air from inside the wall and venting it to the outside. This method is often used in combination with SSD. When planning such systems it is important to distinguish between concrete blocks and the more porous cinder blocks. A skilled and experienced mason may be able to distinguish the two types of blocks once installed visually or by sound after striking them. However, it is difficult for a nonspecialist to distinguish them once installed.

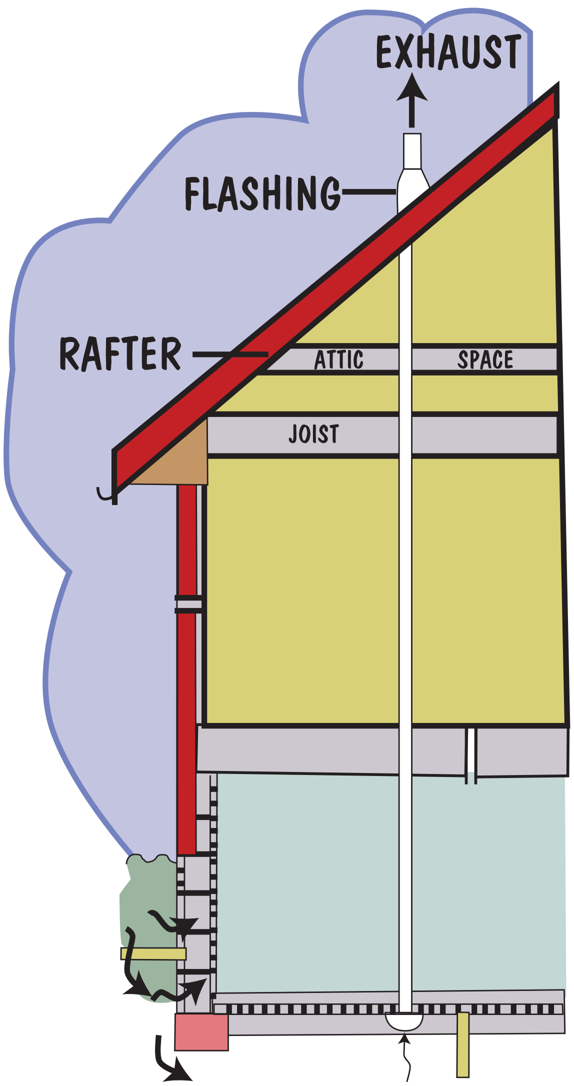
Crawlspace ventilation by depressurization is considered by some to be a variation of SSD technology. Although depressurization can be designed to reduce indoor contaminant levels, it may dramatically increase the crawlspace concentrations making it a potentially high-risk method of mitigation. In contrast, crawlspace ventilation that does not depressurize is a useful mitigation method and is discussed below in the section on HVAC modifications. Instead of crawlspace depressurization, consider submembrane depressurization for crawlspace structures (section 3.3.3) or possibly positive pressure increased ventilation of the crawlspace (section 3.4.3).

SSD and **soil vapor extraction** technologies are closely allied, so site-specific engineering installations may resemble both technologies. NYSDOH guidance (2005) recognizes that soil vapor extraction (SVE) systems which are used to remediate source contamination in the vadose zone away from the building may also be designed to mitigate vapor intrusion. The use of SVE systems may be effective if the radius of influence of the SVE system can be demonstrated to provide adequate depressurization beneath the entire building foundation. In this case, special attention must be paid to the quantity of contaminants exhausted to the ambient air. Conventional SVE systems can increase ambient outdoor air concentrations. Regulation of these systems is described under section 4.3.3 of this document and section 4.4 of ITRC 2007.

3.1.3 Passive Systems

EPA has defined a passive sub-slab depressurization system as "A system designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a vent pipe routed through the conditioned space of a building and venting to the outdoor air, thereby relying solely on the convective flow of air upward in the vent to draw air from beneath the slab" (http://www.epa.gov/radon/pubs/newconst.html). We extend this definition of passive systems at the end of this section to include a discussion of systems equipped with a wind driven turbine to supplement convective (temperature driven) flow.

The passive stack (vent pipe) produces a reduced pressure zone below the building, intended to prevent radon or VOC-bearing soil gas from entering the building. This process is driven entirely by the surrounding environmental conditions. Since mechanical devices do not control the system, understanding the effects of wind and stack height on overall performance is crucial. For more information, see http://baba.astro.cornell.edu/research/radon/.



Passive New Construction

Figure 5. Passive venting system design. (Source: Illinois Department of Nuclear Safety, Guide to Radon Mitigation, http://www.state.il.us/iema/radon/pdf/guidetoradonmitigation.pdf).

While passive systems derive some benefits from stack height and wind velocity, the primary driving forces originate from the buoyancy of the air that is warmed by passing through the heated indoor space. Since these driving forces are relatively small, all piping should be large diameter and risers should rise vertically from the collection point with as few bends in the pipe as possible, such as that shown in Figure 5. Bends in the pipe result in a drag on flow equating to a pressure drop: because the system is based on transient environmentally-induced pressures, minor design inefficiencies translate into potentially significant compromise of system performance. Furthermore, during cooling season these systems may not provide significant flow or in the worst case could even be subject to a small reverse stack effect.

Since the same environmental factors that pull the contaminated soil gas into the building are instrumental in driving the passive mitigation stack, a successful passive stack must be significantly more efficient at extracting the contaminant from the sub-slab region than the building itself. If there are significant gaps in the building envelope the building has a competitive advantage by directly communicating with most of the soil beneath. The passive stack must extend its communication from the suction point outward to all critical points under the building by extending a dominant negative pressure field to those points. Thus a passive system may need more collection points than an active system to be effective, which reduces the capital cost advantage of the passive systems.

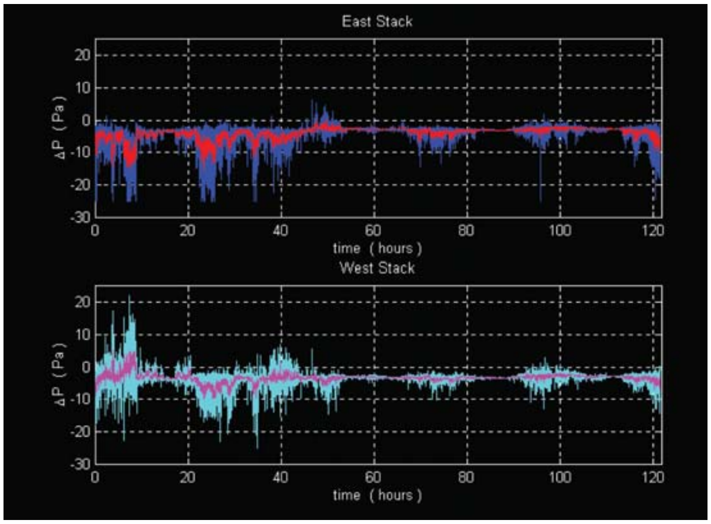


Figure 6. Example of severe pressure transience in a passive system.

Three aspects of passive system performance are illustrated by Figure 6 (Cody 2006). In this example, first note that passive system performance may depend upon the location of the stack or riser relative to building features such as rooflines. In this case, the difference in stack performance solely as a function of location (east and west) is dramatic at some times—such as between 0 and 20 hours when the west stack pressure is often positive. Second, the system shown in Figure 6 demonstrates severe transience. Although the system may transiently reach depressurizations on the order of 20 or 25 Pa, the average depressurization over time is only around 4 Pa at the suction point. Recall that to effectively compensate for typical building depressurizations, active systems are required to achieve a 4-10 PA difference *over the entire building footprint*. In this case, the approximate 4 Pa average depressurization at the stack is unlikely to translate into a 4 Pa depressurization at distances away from the stack. Typical active systems have 250–300 Pa negative pressure at the suction point. In many cases, even this pressure difference will not yield 1 Pa at the slab perimeter. Third, although the east stack averages a negative pressure over the period of measurement, the west stack exhibits a substantial positive pressure much of the time. Positive pressure indicates the direction of airflow is from atmosphere to the sub-slab region. This effect could possibly exacerbate vapor intrusion by increasing flow into the house through the slab.

Passive rather than active systems may be chosen when the vapor intrusion issue is less severe. Passive sub-slab systems are relatively easily converted to active SSD/SSV systems if need be. Passive system design should keep in mind the potential need for such conversion. NYSDOH (2005) reports that passive systems are not as effective as active systems and their performance varies depending upon ambient temperatures and wind conditions. The greatest potential for passive depressurization systems to be effective is with buildings having a good clean layer of aggregate under the slab, a tight slab, and poured concrete foundation walls to minimize air leakage. Passive systems also require more intense and longer term monitoring to validate reliable performance.

Wind turbines may help to increase passive system performance without an ongoing energy cost. Some states describe wind-induced vent systems (Pennsylvania Department of Environmental Resources, not dated, http://www.wpb-radon.com/pdf/PA%20Radon%20Mitigation%20Standards.pdf) which include wind turbines. However, documented long-term performance of these systems is not available at this time.

3.2 Sealing of Penetrations and Entryways

Entryways include: openings in a slab, major cracks in walls, utility penetrations, sump lids that do not fit tightly, and floor drains. Relevant utility penetrations that may need to be sealed include those for plumbing, sewer drainage, HVAC, elevators and in some cases electrical conduit. It can be difficult to identify and permanently seal the places where vapors may be entering, as normal settling of the building opens new entry routes and reopens old ones (Babyak and Welt, 2006). Nevertheless, sealing cracks and other openings in the foundation is a basic part of most approaches to reducing vapor intrusion since it makes SSD systems more efficient. Sealing these openings limits the flow of soil gas into the building thereby making other vapor reduction techniques more effective and cost-efficient.

Both the U.S. EPA (1993b, http://www.epa.gov/radon/pubs/physic.html) and New York's guidance (NYSDOH, 2005) take the position that sealing alone is not a reliable technology, but that sealing is a useful and necessary supplement to sub-slab depressurization.

Sealants are materials used to fill joints occurring between two different materials as well as expansion and control joints. Effective sealants must:

- Have good adherence to building materials
- Be workable at the installation temperature
- Have high elasticity and compressibility to resist foundation movements
- Not shrink after curing
- Be compatible with the VOCs of concern
- Have good recovery after stretching or compression
- Be durable and water resistant
- Be low in emissions of hazardous VOCs

Sealing materials include synthetic rubbers, acrylics, oil-based sealants, asphaltic/bituminous products, swelling cement, silicon and elastomeric polymers. Sealants are sometimes supplemented with fillers or backup materials, including filler rods, tapes and tubing and foams (Dagostino, 1983). Caulking is a type of sealant used in "noncritical joints subject to compressive forces only" (Watson, 1978). Sealants should not be confused with sealers, which are materials used to coat materials (for example a basement wall) to prevent penetration (i.e., of water).

More detailed information is provided in Watson (1978), Dagostino (1983), EPA (1994a), FEMA (1999), in ASTM's Guide for Use of Joint Sealants (ASTM, 1995a) and ASTM's Guide for Use in Selection of Liquid-Applied Sealants (ASTM, 1995b). Practical advice on techniques for applying sealants in residential settings is available from a number of resources on waterproofing including Blackburn (1991) and Reader's Digest (1977).

Sealing or weatherization is frequently recommended for energy cost reduction. Note, however, if the source of indoor contaminants is indoors and not vapor intrusion, reducing the ventilation rate of a structure may result in increased indoor air concentrations.

3.2.1 Utility Penetrations and other Routes of Entry

A utility corridor or utility trench is defined as one or more underground or buried utility lines or pipes, including any excavated and subsequently backfilled trench that the utility line or pipe was constructed or laid in. Utility corridors include, but aren't limited to: sanitary and storm sewers, water lines, gas lines, sewer force mains, buried electric power distribution lines and buried telephone, cable television or telecommunication lines. Utility corridors can be found in public rights of way, including streets or roads, as well as on the properties being served by the utilities. Utility corridors that are of higher permeability or higher porosity than the surrounding soils are of greatest concern as pathways for preferential migration. At such sites, vapors or free product could migrate within a utility corridor regardless of the groundwater depths. Flow through utility corridors could be advective depending on pressure gradients or diffusive which is independent of pressure gradients. Furthermore, vapors could migrate in any direction, while free product may tend to migrate in the down slope direction along a trench (Wisconsin, 2000).

Utility penetrations through the walls of a structure are of concern because they often provide a direct connection between the living space and the subsurface soil/sub-slab soil gas. Concern arises because the construction of subsurface utility corridors (utility annulus) is often surrounded by high permeability gravel. Accordingly, free product or vapor migrating along a utility corridor could move toward and into buildings that are serviced by or connected to a utility. Explosive vapors or flammable free product in utility corridors may present an emergency situation and thus must be addressed upon discovery. NJDEP 2005 recommends that all potential pathways/defects (e.g., cracks, sumps, utility lines) should be sealed during building walkthrough/initial sampling/assessment. Examples of how utilities tie into various types of structures are shown in Figure 2.

Most municipal and homeowner's association utilities maintain water and sewer system maps, which normally show the location and depths of sanitary and storm sewers, water mains and sewer force mains (pipes carrying the pressurized flow output from a sewage pumping or lift station). Such maps also normally show the locations of sewer manholes, sewer and trench slope, water main valves and fire hydrants, which are helpful to the investigator when locating utility corridors in the field. However in other communities documentation of historically installed infrastructure may be incomplete.

Other relevant information can include plans of the specific building being studied, utility maps, soil maps, results from other nearby investigations and historical use maps, including Sanborn insurance maps and the U.S. Geological Survey (USGS) topographic maps. Combining general knowledge of the extent of a release, soil and groundwater conditions in the site area with examination of actual utility maps can help the investigator develop a conceptual model and make an initial determination of whether utility corridors may be potential migration pathways that would require special treatment.

Generally, sewers and water mains are deeper than gas, electrical and telecommunication lines and sewer lines are normally routed below water lines. Where maps showing utility depths are unavailable or unreliable, it may be possible to measure the depths of utilities by dropping a tape measure down an access point, such as a sewer manhole or telecommunications access. Materials of construction are normally known, and sometimes bedding and backfill materials are known (Wisconsin, 2000). Most states have a "one call" or similar utility locator service that must be notified before intrusive work. See, for example: Risk Management Services™ (http://www.rmlibrary.com/sites/safetdigsa.php) or Construction Weblinks™ (http://www.constructionweblinks.com/Industry_Topics/Specifications__Technical_Data/Specifications_and_Technical_D/Earthwork_and_Site_Work__Speci/underground_alert_centers/underground_alert_centers.html)

Placing utility dams can control vapors migrating along utility corridors. Utility dams (a.k.a. trench plugs or trench saddles) are temporary or permanent barriers installed at regular intervals in utility trenches. These dams are used for preventing erosion and for minimizing the potential of groundwater seeping along the path of least resistance, along pipes and other utility lines in the trench. They are generally one to two feet long and composed of clay or pelleted bentonite because it has very low permeability and excellent sealing properties. (http://www.pacd.org/products/bmp/trench_plug.htm), (ASTM E 2435-05).

The use of bentonite as a sealant is an established technology, primarily associated with well drilling and management. However the effectiveness of bentonite in blocking vapors (as opposed to water) may not be fully established. One example project was identified where a trench dam was specified as a barrier for landfill gas. Specifications included:

- Trench dams should be installed immediately adjacent to the exterior perimeter of the building foundation,
- Trench dams should have a minimum length of 36 inches or twice the width of the trench,
- Trench dams should be of a bentonite cement slurry—a mixture of 4 percent Type II cement and 2 percent powdered bentonite. (Forbort, 2006)

Potential vapor intrusion along utility lines can also be addressed at the building envelope using sealing techniques. These sealing methods include mechanical techniques (such as gaskets), sealants, and caulking (see discussion above). Information regarding sealing air leaks in building envelopes is available in the following locations:

- Department of Energy Technology Fact Sheet. http://www.toolbase.org/PDF/DesignGuides/doe_airsealingFS.pdf a Department of Energy primer with useful diagrams and discussion of sealing materials
- Oregon Residential Energy Code. http://www.oregon.gov/ENERGY/CONS/Codes/docs/res14.pdf similar energy oriented information from the State of Oregon
- Alaska Housing Manual, 4th Edition. http://www.ahfc.state.ak.us/reference/housing_manual.cfm The Alaska housing manual, though tailored for an extreme climate, provides much useful and well-illustrated material on sealing in chapters 2, 4, 5 and 8.
- Habitat for Humanity, St. Louis. http://www.habitatstl.org/construction/cstmanual/airsealing/ contains practical hands-on information from a volunteer organization.

3.2.2 New Construction and Repairs

Most of the material covered in the preceeding sections also applies to sealing the building envelope during new construction. Indeed, sealing during new construction generally should be easier and cheaper than a retrofit (Welt and Thatcher, 2006), and there is a greater opportunity to use membrane (passive) barriers (see below). Attention must be paid however to sequencing the trades involved in construction so that one contractor does not undo the sealing provided by another. EPA provides extensive information on radon resistant new construction that can readily be adapted to vapor intrusion issues for organic contaminants by ensuring that the materials used are resistant to diffusion of the contaminant of interest and are durable in the presence of those contaminants.

- For residences see http://www.epa.gov/radon/construc.html and http://www.epa.gov/radon/pubs/newconst.html.
- For schools see http://www.epa.gov/iaq/schooldesign/controlling.html and http://www.epa.gov/ORD/NRMRL/pubs/625r92016/625r92016.htm.
- For large buildings see U.S. EPA Radon in Large Buildings http://www.epa.gov/ORD/NRMRL/pubs/625r92016/625r92016.htm.
- For other building types see ASTM's "Guide for Application of Engineering Controls to Facilitate Use or Redevelopment of Chemical-Affected Properties" (ASTM, 2005)

Repairs to masonry and concrete work may be necessary for basement walls, slabs and floors. Standard techniques discussed above that were designed for structural, waterproofing and/or aesthetic repairs can be adapted, but air tightness against pressure is more difficult to achieve than aesthetic or structural repair.

3.3 *Passive Barriers (including Membranes)*

Both sheeting products and poured/cure-in-place products provide a passive, physical barrier to vapor intrusion. It is also possible to use clay barriers for this purpose in new construction (Geyer, 2006).There are two main types of passive barriers that will be discussed in this section: sheet membranes and fluid-applied membranes. Later in the section we will provide general information on installation and information about the membranes used as part of submembrane depressurization systems, typically for crawlspaces.

3.3.1 Sheet Membranes

Sheet membranes are usually 40–60 mil high-density polyethelene (HDPE) but can be polyethylene, polyvinylchloride, or EPDM (ethylene propylene diene monomer) rubber. Sheet membranes less than 30 mil (e.g., 6 mil visqueen) are not durable enough to prevent significant damage during placement of reinforcing steel and concrete and thus are not recommended in sub-slab applications. An example of how a membrane is typically installed is shown in Figure 7.

3.3.2 Fluid-applied Membranes

Fluid-applied or cured-in-place membranes are spray-applied to a specific thickness (e.g., 60 mil). One of the major vendors of cured in-place products reported that to their knowledge there have not been any studies of the effectiveness of these products published in the literature or presented at conferences (Ameli, 2006). Nor has any formalized testing taken place at a whole structure scale. However the vendor does have numerous case studies of applications as gas vapor barriers for methane, chlorinated solvents and petroleum hydrocarbons available at their websites (http://www.liquidboot.com/index-gasvapor.php; http://www.polyguardproducts.com/products/Underseal/index2.htm).

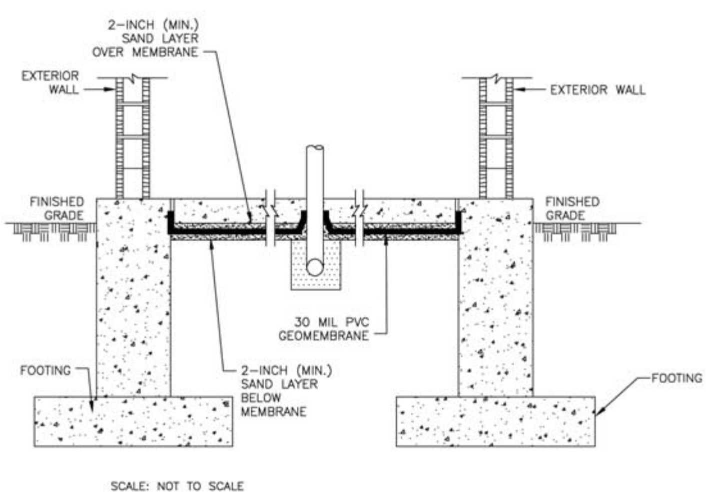


Figure 7. Membrane barrier installation example.

3.3.3 Membranes Used in Membrane Depressurization Systems

In buildings with a crawlspace foundation, a membrane may be used to install a sub-membrane depressurization (SMD) system and is recommended in the state of New York's guidance. NYSDOH (2005) recommends a membrane of polyethylene or equivalent flexible sheeting with a minimum thickness of 6 mil or 3 mil cross-laminated. These thicknesses may not even be adequate if the membrane will be heavily trafficked. The sheet should cover the entire floor area and be sealed at the seams and penetrations. During the installation the sheeting should not be pulled tight, because when the depressurization system is turned on, it will be drawn down which may cause strain on the seals. Smoke testing is used after installation to ensure a good seal (see section 5.5.1). Getting a good seal around pipe chases and other protruding objects can be problematic when using sheeting and the vendors of spray-on type membranes do not suggest mixing the two types of barriers. Additional information can be found in ASTM's "Specification for Plastic Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs" (ASTM, 1993). This technology is discussed in depth in section 3.6.1.

3.3.4 Installation of Membranes

Some discussion of techniques for installing membranes and seals around penetrations in existing structures is provided in section 2.2.2.1 of EPA's "Air/Superfund National Technical Guidance Study Series: Options for Developing and Evaluating Mitigation Strategies for Indoor Air Impacts at CERCLA Sites" (EPA, 1993a), in section 4.2.2 of the New York Guidance (NYSDOH, 2005) and in section III.2 of the California guidance (http://www.dtsc.ca.gov/AssessingRisk/upload/HERD_POL_Eval_Subsurface_Vapor_Intrusion_interim_final.pdf).

We recommend that the integrity of all membranes be verified not only at the time of membrane installation but also later after foundation and floor system construction is complete. Multiple test times are suggested because the cost of repairs is lower the sooner the problem is identified and post membrane installation construction work can damage a previously acceptable membrane. All sheet products should be protected from ultraviolet (UV) damage such as from sunlight.

New construction is a good time to install a membrane but performance is only as good as the quality of seals that can be achieved and maintained at utility penetrations. The installation of the membrane must be the last step before pouring the slab. Experience has shown that it is almost impossible to maintain a membrane without penetrations at an active construction site during the building process. Boots are required at all penetrations through the membrane. Boots are sheaths or coverings that seal the membrane to vertical objects such as pipes, utility chases, wires. The manufacturer of the geomembrane typically has a quality assurance manual that specifies the procedure for correct installation. This manual should be requested and reviewed. This topic is covered in EPA's "Model Standards and Techniques for Control of Radon in New Residential Buildings" (EPA, 1994a). ITRC (2007) recommends preparation of a detailed quality assurance/quality control (QA/QC) plan covering situations that could damage the membrane during installation and subsequent construction activities.

3.4 Natural Ventilation and HVAC Modification

In this section we will present information on a number of approaches to vapor intrusion mitigation through modifying building ventilation. Passive and active ventilation changes for the living space are discussed first followed by ventilation changes applied to crawlspaces. Extensive additional information on ventilation and HVAC systems can be found at:

- http://www.buildingscience.com
- http://eetd.lbl.gov/ied/viaq/v_pubs.html
- www.buildingamerica.gov

An aspect of ventilation is providing a dedicated air supply for combustion appliances, etc., to reduce indoor air depressurization. A dedicated air supply for combustion appliances is a good practice for avoiding backdrafting of the appliances. This approach usually has a modest effect on the indoor pressure.

3.4.1 Increase Passive Ventilation of the Occupied Space

Some natural ventilation occurs in all buildings. By opening windows, doors, and vents, ventilation increases. This increase in ventilation mixes outdoor air with the indoor air containing VOC vapors, and reduces indoor levels of the contaminants. However, as discussed in section 2.2 if a building is experiencing a "stack effect", which is normal, opening a window only in an upper story above the neutral pressure plane can increase the inflow of soil gas and thus be counterproductive. Moreover, once windows, doors, and vents are closed, the concentration of VOCs most often returns to previous values within about 12 hours. Thus, natural ventilation in any type of building should normally be regarded as only a temporary reduction approach (Babyak and Welt, 2006) because the increased cost of heating or air conditioning will lead to closing the doors, windows or vents.

3.4.2 Active HVAC Adjustments in the Occupied Space

Sometimes HVAC modifications are made to maintain adequate positive pressure within at least the lowest level of a structure (and all levels in contact with soil) to mitigate vapor intrusion. Older structures, however, rarely exhibit the requisite air tightness to make this approach cost effective. If sufficient positive pressure within the structure can be consistently maintained, then advective flow from the subsurface into the structure should be effectively eliminated although diffusive flow may continue. Most forced air heating and cooling systems only operate as needed. This system would need to be modified to run continuously when used to maintain a constant pressure within the structure. In addition, some buildings do not have forced air systems. For example, many structures in the northern U.S. are heated with hot water circulation systems (radiators) and may lack air conditioning.

Some building operators assert that vapor intrusion can be largely avoided in commercial structures by complying with ventilation codes. For example, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) publishes standards such as:

- ASHRAE Standard 62-1989 "Ventilation for Acceptable Indoor Air Quality"

- ASHRAE Standard 90.1-1989 "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings"
- ASHRAE Handbook (1985) Fundamentals. Chapter 22. Atlanta, Georgia. American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE). 1985.

Ventilation standards also exist in some jurisdictions such as:

- Washington state http://www.energy.wsu.edu/documents/code/2003VIAQ.pdf
- Massachusetts http://www.mass.gov/Elwd/docs/dos/iaq/iaq_392_mechanical_vent.pdf
- Minnesota http://www.doli.state.mn.us/pdf/bc_2007msbc.pdf and http://www.health.state.mn.us/divs/eh/iarc/vent.html

Compliance with the provisions of those codes, that require a minimum amount of fresh air to be provided, will assist in minimizing vapor intrusion. Specifically, if a positive pressure differential can be maintained consistently between the interior and sub-slab air vapor intrusion will be minimized. Note, however, that existence of a positive pressure differential between interior and exterior of a structure is not sufficient, since exterior and sub-slab pressures can differ. Nor are measurements of positive air flow into a structure sufficient to demonstrate a pressure differential across the slab.

Note also that ventilation code standards have not always existed in the past when many existing structures were built, and compliance is normally required only for new construction and/or significant rehabilitation. Anecdotal evidence also suggests that "ventilation codes" may not effectively govern the ongoing operation of HVAC systems in small commercial structures.

Berry-Spark, et al. (2006) describes a former manufacturing facility that has been redeveloped for use as a multi-unit commercial building where TCE was the pollutant of concern. An HVAC adjustment to positively pressurize the building resulted in an increase in the AER of a factor of two (using post-modification positive pressure measurements). The average pressure differential was measured to be 0.01 to 0.08 inches of water (2.3 to 19.8 Pa). Two rounds of indoor air samples were collected about 5 and 6 weeks after the HVAC adjustments were made. These show an order of magnitude reduction in the contaminant was achieved. Dilution associated with the factor of 2 increase in AER accounts for a factor of 2 decrease in the concentration, which is only 20 percent of the total decrease. By deduction, the additional 80 percent reduction must be due to reduced negative pressure in the building. By increasing the AER, the costs of heating and cooling would also increase substantially.

Methods that rely solely on increasing AER/ventilation in the occupied space without pressurization can achieve only modest reductions in concentrations (50–75 percent). Further increases in ventilation rates usually become uncomfortable for occupants. (CIRIA, 1994)

3.4.3 Crawlspace Ventilation

This section applies to crawlspaces that are substantially enclosed. Crawlspaces that are freely ventilated (i.e., construction on piers) will rarely need mitigation unless the piers themselves are hollow. Foundations without effective cross ventilation (i.e., piers on only one side) could need mitigation.

Levels of VOCs in enclosed crawlspaces can be lowered by ventilating passively (without the use of a fan) or actively (with the use of a fan). When a fan is used it should blow into the space rather than out, to positively pressurize the crawlspace and thus minimize concentration in the crawlspace. However, use of ambient air for this purpose in cold climates could cause problems with pipe freezing. Crawlspace ventilation may lower the concentration of vapors in the indoor air both by reducing the building's suction on the soil (via a pressure increase in the crawlspace) and by diluting the concentration of vapors in the crawlspace.

Opening vents or installing additional vents achieves passive ventilation in a crawlspace. In colder climates, during either passive or active crawlspace ventilation, water pipes, sewer lines and, appliances in the crawlspace may need to be insulated against the cold. These ventilation options could also result in increased energy costs for the building (Babyak and Welt, 2006). Since it is common to recommend to homeowners that these vents be closed at some seasons of the year, it would be difficult to rely on natural crawlspace ventilation as a long-term remedy through changes at building occupants Skirted areas under mobile homes can also be opened or ventilated for dilution to limit vapor intrusion. Ventilation systems, however, should be designed not to negatively pressurize these spaces with respect to soil gas. These techniques are discussed in section 2.2.3 of EPA 1993a and sections 7.2 and 7.3 of "Reducing Radon in Schools: A Team Approach" (EPA 1994b), among other sources.

Active crawlspace ventilation involves blowing air directly into the crawlspace using a fan and can be combined with sealing. This technique generally does not work as well as sub-membrane depressurization. It is important to seal the unoccupied crawlspace from other portions of the building. This engineering control method may result in increased energy costs due to loss of conditioned air from the building (Babyak and Welt, 2006). Crawlspace venting that causes depressurization is not recommended because it results in increased concentrations in the crawlspace.

3.5 Air Cleaning using Adsorbents, Scrubbers or Photocatalytic Oxidation

The devices discussed in this section aim to mitigate vapor intrusion by directly treating air in the structure, as opposed to blocking entrance or increasing ventilation. Available air cleaners include both in-duct models and portable air cleaners. These devices operate on various principles including zeolite and carbon sorption, ozone oxidation and photocatalytic oxidation. (Note, however, that some regulatory agencies have taken strong positions to warn of potential problems with air cleaners dependent on ozone generation: http://www.arb.ca.gov/newsrel/nr012005.htm). Methods that inject ozone into the breathing space of the indoor environment cannot be recommended as an air cleaning technique, as ozone is a criteria pollutant. The state of California has banned the sale of residential ozone producing air cleaners effective in 2009. Methods that rely on adsorption such as zeolites and carbon generate a waste that must be disposed of appropriately or regenerated.

While the literature on the efficacy of air cleaning devices for vapor intrusion is quite limited, literature has recently been published regarding use of these devices for indoor air contaminants originating from other sources, or from undetermined sources. Much of this work focuses on pollutants not normally encountered in vapor intrusion—such as particulate matter. However, tests have been conducted that showed some efficacy for certain VOCs such as:

- Formaldehyde—test chamber scale. (Nozaki, et al., 2005 and references cited therein)
- Decane—field scale, multiple real buildings (Howard-Reed, et al., 2005)
- Acetone—field scale, single real building (Kwan, et al., 2005)

Henschel (1998) has conducted an economic analysis comparing photocatalytic oxidation to activated carbon systems for TCE, formaldehyde, acetone, benzene and toluene which concluded that for most contaminants activated carbon was more cost effective. UV-photocatalytic oxidation is considered an attractive technology because it typically converts most VOCs into carbon dioxide (CO_2) and water under indoor air conditions. TCE photocatalatic oxidation yields hydrochloric acid as well which is undesirable (Dibble and Raupp, 1992). However, according to Chen, et al., (2005), the commercialization of this technology as room cleaners is still in the beginning stage.

Section 2.2.3.2 of EPA (1993a) includes a discussion on air cleaning. Readers are also referred to another study: "Performance of Air Cleaners for Removing Multiple Volatile Organic Compounds in Indoor Air" (Chen, et al., 2005). According to this study, sorption filtration is still the most effective off-the-shelf commercial technology, at least for the initial period, for general removal of indoor VOC pollutants. Sorption filter design plays an important role: generally filters with more surface area and better air-to-sorbent contact had higher efficiencies.

Berry-Spark et al., (2006) describes testing at an occupied residence that is located down gradient from a former industrial facility where TCE had been released. The TCE is now present in soil and groundwater. A commercially available residential air filter with an 18-lb impregnated activated carbon filter cartridge was installed in the basement to remove the VOCs from the indoor air. It is suggested that this is a good alternative where a shallow water table may make sub-slab venting difficult. Data are presented in this paper that appear to show substantial concentration reductions although only one background-sampling round was presented. Operation of the filter has generally reduced TCE and TCE daughter product concentrations in the indoor air below detection limits of 1 to 2 $\mu g/m^3$. Note that two detections occurred which are thought to have resulted from impeded air circulation due to doors being closed. This result would suggest such systems require careful monitoring.

In another study (Daisey and Hodgson, 1989), four different air cleaners were tested in a room-sized chamber. Two of these devices were effective in removing five of the six VOCs tested. Two devices were not very effective. Effectiveness was believed to relate to the amount of activated carbon in the devices and their flow rates. Both effective devices had a flow rate of around 227 m^3/hour, while the key component was an activated charcoal filter. The VOCs that were successfully removed include: 2-butanone, n-heptane, toluene, tetrachloroethylene, and hexanal. Nitrogen dioxide (NO_2) was also tested and removed. None of the devices could remove dichloromethane. The removal rates and efficiencies decreased substantially after 150 hours of operation. There was also evidence of chemical reactions occurring in the carbon after extended operation.

3.6 Combinations of Multiple Technologies

Depending on site-specific conditions, it may be desirable to combine one or more of the above technologies to improve efficiency or reduce cost. For example sealing and other barrier approaches can be effectively paired with sub-slab depressurization strategies and are often considered part of that technology. Combinations of technologies can be installed together or applied in a phased approach, based on certain risk related triggers.

For example, passive systems can be used with vapor-resistant features (i.e., passive barriers) installed in newly constructed homes where the water table is well below the gravel layer and vapor barrier (Babyak and Welt, 2006). Active SSD systems in conjunction with passive membrane barriers would be even more effective (EPA, 1993b).

3.6.1 Sub-membrane Depressurization

In buildings with a crawlspace foundation, a membrane may be used to install a SMD. A membrane similar to those described above is placed on the ground in the crawlspace to retard the flow of vapor into the building. The membrane is sealed to the walls of the building and one or more suction points are fitted through the membrane, using a plywood or plexiglass gasket. The gasket is manufactured by sealing the plywood (or other suitable material) to both sides of the membrane (below and above). A pump or fan is then connected to the suction point(s) and the system is operated in a manner similar to the SSD system; that is, the SMD system uses a suction point(s) and manifold to draw vapors from beneath the membrane and vent them to the atmosphere. The lower pressure beneath the membrane prevents vapors from entering the building. Additional design recommendations for these systems can be found in:

- ASTM E 2121-03 especially Section 7.3.8
- Chapter 8 of EPA 1993b
- Chapter 4 of NYSDOH 2005
- Section 2 of the Florida (1995) guidance

The state of New York's guidance calls for the use of sub-membrane depressurization systems in crawlspaces.

4 SELECTING A TECHNOLOGY

The process of selection, design, sizing, and installation of vapor intrusion mitigation technologies is similar to most other technologies (Figure 3 provides an overview flowchart). First and foremost, the objective of the technology must be clearly defined and quantified (this aspect is discussed in more detail in sections 5.1 and 5.2). Next, specific inputs must be identified and bounded to narrow the selection to one choice, consisting of a distinct technology or a combination of technologies. This is an iterative process, however some criteria and input parameters are more important than others.

Vapor intrusion and other indoor air issues are driven by concerns about the health of the building occupants. Thus, the primary input that governs the selection of the appropriate technology or combination of technologies should be based on the required reduction target(s) or acceptable air concentrations for the contaminants. These reduction targets must be reached not only in the short term, but they should also be sustainable over the long term (i.e., the life of the building or the duration of the vapor source, whichever is shorter). Therefore, the second input to select a technology is reliability. Reliability may be defined here as having three components:

- The system should consistently produce acceptable indoor air quality according to the required targets.
- The system should not break down and failures, if they occur, should be readily perceived and easily remedied.

- The system should be robust (resistant to harm from reasonably foreseeable events occurring around it).

When assessing reliability and appropriateness of a vapor intrusion mitigation system, it is important to keep in mind that the system is likely to be impacted by people who may not be fully cognizant of the system's intent. When the system is noisy or consumes significant energy, it may be turned off. Vents or windows may be opened or closed, altered or blocked. Continued reliability and effectiveness should be optimized through information dissemination and training, or through other means, such as deed restrictions or monitoring schemes.

The third input to consider in selecting a technology is the determination of any negative effects that the technology may have on other indoor air quality parameters. If a vapor intrusion technology significantly compromises other aspects of indoor air quality (e.g., moisture content or perceived ventilation rates), it will be unacceptable. Information on the impact of ventilation rates on perceived air quality can be found at http://eetd.lbl.gov/ied/viaq/v_rates_6.html. Similarly, acceptable ambient air quality outside the structure must be maintained.

If a proposed system has "passed" the above threshold criteria, the fourth input that will influence selection is the physical structure of the building, including:

- Intended use (commercial, industrial or residential)
- New vs. existing building
- Foundation type (slab, basement, crawl space, mobile home)
- Type of HVAC system

The fifth input to take into consideration in the selection process is cost, which may be broken down into:

- Capital cost
- Installation cost
- Operation and maintenance cost
- Monitoring cost

Because vapor intrusion is an issue that affects the public directly, especially in residential structures, communication with the public is very important. A final factor to be considered is the ease of public acceptance. This issue is addressed in the section entitled "Risk communication and stakeholder involvement considerations," below.

4.1 Concentration Limits for the Contaminant

The primary driver for selection of a best mitigation technology will be the calculated or numeric risk-based standard for the indoor exposures. In some states numeric standards for indoor air have been developed as a matter of policy or regulation for vapor intrusion. In such cases, acceptable mitigation technology would achieve those indoor air standards. In other states (e.g., Connecticut, Massachusetts), allowable concentrations in other environmental media (e.g., soil gas or groundwater) have been derived to be protective for vapor intrusion. In most cases, the regulations for such standards provide for the installation of mitigation systems for buildings in cases where rapid remediation of soil and groundwater is technically impracticable. The selected mitigation technology should then achieve the performance standards set out in the regulations (or policies). Note: such performance standards may presume that institutional controls will be implemented to ensure long-term stewardship of such sites until remediation is achieved.

In some jurisdictions, specific numeric standards may not be available. Typically in these cases, a site-specific risk-based standard is determined based on an unacceptable health risk. A selected mitigation technology should then achieve a reduction in COC concentration in indoor air to the required risk-based level.

Obviously, whatever technology is selected must be able to meet the applicable numerical contaminant standard. Note that available radon literature supports the premise that few techniques other than active sub-slab depressurization can achieve two orders of magnitude reduction in vapor intrusion. Thus alternatives such as sealing should likely be used only as stand-alone options when a lower level of reduction is acceptable, such as when no demonstrated risk exists but proactive precautions are being taken.

Other characteristics of the COC that may be relevant to selecting a technology include:

- Flammability
- Toxicity
- Corrosiveness/incompatibility with certain materials from which the mitigation system may be constructed.

4.2 Reliability

Because the reduction goals must be met consistently over long periods of time, reliability is an important criterion for selecting vapor intrusion mitigation technology. While most of these technologies are considered mature (i.e., they have been used extensively for other applications such as radon or moisture control), it is advisable to thoroughly query the vendor or consulting engineer on this issue.

Of special consideration is operational robustness. The system should be robust in that the performance of the system is not negatively affected by actions of the occupants that arise from use of the building (e.g., opening or closing of basement doors or windows, crawlspace vents or routine minor home maintenance). Occupant activities are important when components of the system are readily accessible, as with air purification equipment or with HVAC modifications.

4.3 Effect of the Technology on Other Aspects of Indoor Air Quality

Designers must be aware that indoor air quality is a holistic concept that may require more than just minimization of the concentration of volatile organics contributed by vapor intrusion. Appropriate levels of humidity, temperature, carbon dioxide, carbon monoxide, particulates/dust, mold, allergens and airflow must be maintained. Other potential sources of volatile organics in the indoor environment also must be taken into consideration including environmental tobacco smoke, cleaning agents, solvents, glues and paints.

4.3.1 Moisture Infiltration and Vapor Intrusion—A Complex, Critical Relationship

Moisture infiltration into a structure, whether or not the moisture is contaminated, presents a multifaceted problem for indoor air quality and thus should be addressed. When contaminated groundwater is shallow enough to infiltrate a building, it presents both a contaminant vapor intrusion and mold risk. Even in those cases where groundwater does not directly intersect a building and sub-slab soils may appear dry, infiltration of soil moisture can pose an equally significant mold threat because soil gas is typically at 100 percent relative humidity (Springer 1995). There is a symbiotic and sometimes complex relationship between mitigation of moisture problems and mitigation of vapor intrusion:

- Sealing the building envelope and dewatering the sub-slab area would be expected in many cases to reduce both moisture infiltration and vapor intrusion.
- Gravel beds or sub-slab mats originally installed for moisture control provide permeable layers for air flow and thus aid in the installation of sub-slab ventilation systems.
- Water saturation of the full thickness of gravel beds or sub-slab mats can dramatically interfere with airflow, rendering portions of a sub-slab system ineffective.
- Water can also cause the typical pumps used in sub-slab depressurization systems to work too hard and burn out.
- Drains and sumps may be preferential routes for entry of contaminant vapors.

The intrusion of contaminated groundwater directly into the structure is considered by some to be a separate matter from vapor intrusion (NJDEP, 2005). In many cases, there will be a residual vapor intrusion problem after the contaminated ground water intrusion has been addressed.

Moisture problems can be addressed with drainage modifications to the lot, drainage systems along the foundation, or damp proofing of the foundation/basement walls. The engineering practice in the area of moisture resistance and moisture control is well developed. See, for example, "Construction Dewatering," (Powers, 1992), which includes a chapter on water management in contaminated construction sites, as well as discussion of drains, sumps, pumps, etc., for structures. Moisture exclusion technologies in construction are also well documented. See, for example, http://www.toolbase.org/techinv/techDetails.aspx?technologyID=165). Elimination of human exposure to contaminant-affected groundwater is also covered in ASTM (2005), for example, in section 6.2.4 and appendix X3.

Practical recommendations on moisture control techniques for residential settings are available from a number of resources, including:

- http://www.epa.gov/iaq/homes/hip-moisture.html

- http://www.buildingscience.com/buildingphysics/moisturecontrol/.
- FEMA 312 "Homeowners Guide to Retrofitting" covers various strategies such as wet floodproofing, elevation, building relocation, and dry floodproofing. FEMA 312 can be accessed from http://www.fema.gov/library/index.jsp.
- http://www.extension.iastate.edu/Publications/PM1561.pdf
- http://server.age.psu.edu/extension/factsheets/d/D12.pdf
- Blackburn (1991)
- Reader's Digest (1977)

Control of moisture attributable to contaminated groundwater infiltration is likely to reduce but not eliminate the potential for transport of contaminants into the structure. If the groundwater is lowered by pumping or improved drainage, the usual entry mechanisms for contaminated soil vapor will still be operative. As a side benefit, whatever the source of the observed moisture, control to accepted humidity levels will improve air quality by reducing the potential for mold growth.

Modifications to the HVAC system of the building for the purpose of mitigating vapor intrusion problems should be designed with careful attention to avoiding condensation of water resulting from excessive humidity. Excess moisture can foster the growth of mold, which has significant negative impacts on indoor air quality and potentially the health of building occupants. Added HVAC capacity must have effective water drainage from the cooling coils. Conversely, in some climates HVAC modifications might lead to uncomfortably low levels of humidity.

4.3.2 Effects of Changes in Air Circulation/Air Exchange

If significant sources of VOCs exist within the occupied portion of the space due to resident/occupant activities, increased building ventilation may well be beneficial. Other mitigation approaches such as material substitution, changes in use practices or localized ventilation may also be necessary in those cases, but are beyond the scope of this paper.

On the other hand, changes to air flow can cause unanticipated moisture problems due to condensation at the building envelope or due to insufficient ventilation of interior moisture sources (http://learningstore.uwex.edu/pdf%5CB3783.pdf; http://www.uwex.edu/news/2003/10/solving-winter-home-moisture-problems-by-john-merrill-university-of; http://extension.oregonstate.edu/catalog/pdf/ec/ec1437.pdf). See information in section 2.2.3.1 of EPA 1993a for a discussion of some additional effects of ventilation.

The effects of induced pressure/ventilation changes should be carefully evaluated in any home with combustion appliances such as heating, clothes drying and/or cooking systems. These systems usually draw their combustion air from the indoor airspace. Thus, it is essential that depressurization systems for mitigation of indoor air not cause backdrafting (induced spillage of combustion gases) of combustion devices in the structure (NYSDOH, 2005). Backdrafting can release deadly combustion byproducts into the structure. The various available backdrafting tests generally involve setting appliances, HVAC systems, etc., for the worst case negative pressurization anticipated for the building. Then a carbon monoxide or flow visualization test is performed for backdrafting at each stack for a combustion device in the home. Detailed recommendations on these issues including testing procedures are provided in section 11.5 of EPA 1993b and in ASTM E1998 "Guide for Assessing Backdrafting and Spillage from Vented Combustion Appliances." For more information on the general issue see http://www.epa.gov/iaq/homes/hip-combustion.html.

4.3.3 Effects of Engineered Systems on Ambient Air Quality

The broader impact of VI systems that could increase the concentration of VOCs in the community's ambient air (for example, active or passive sub-slab ventilation) should be considered. Consideration of this issue is especially important where pollutants are acutely toxic, local meteorology does not facilitate dispersion, vented concentrations are unusually high, multiple systems are being installed in a densely populated area or other factors limit the allowable stack height. Good engineering practice requires outlets from a venting system (pipe ends) not be close to a window or allow for the vapors to re-enter the building (ASTM E 2121, ASTM E 1465-92). In some cases mass loading calculations or dispersion modeling may be appropriate to analyze the potential impact of reentrainment.

This issue is not unique to vapor intrusion mitigation systems. Similar issues have been analyzed for years for remediation technologies such as soil vapor extraction or air sparging. However, the systems for vapor intrusion mitigation are more likely to be located in residential areas. EPA's Air Toxics Regulations [which are also known as national emission standards for hazardous air pollutants (NESHAPs) or maximum achievable control technology (MACT) standards] should be consulted. Under the site Remediation MACT, a facility is required to review a series of exemptions and, if none of them applies, then the MACT limits apply. New, reconstructed, and existing remediation systems must meet the following criteria for the MACT to apply:

- The site remediation activity is collocated at a facility that has other sources that are individually or collectively a major source of hazardous air pollutants (HAPs)
- A MACT activity, which is an activity in a source category given by Section 112(c) of the Clean Air Act, is performed at the facility

The rule excludes remedial activities at gas stations for the purposes of cleaning up remediation material from a leaking underground storage tank, or that are located at farm sites and residential sites. Remedial activities occurring under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program (Superfund) and as corrective action under the Resource Conservation and Recovery Act (RCRA) to clean up hazardous substances, hazardous wastes, and hazardous contaminants are also excluded. If the MACT limits apply, then the limits can be met via control devices or other means. As a broad rule of thumb, if the MACT applies and emissions of an individual hazardous air pollutant are above 3.0 lb/hr and 3.1 tons per year (TPY), you must reduce emissions via controls or work practices. In many cases the air emissions from these systems are found to be below regulatory limits, but in other instances emission control devices may be required. Generally, systems are screened against these Clean Air Act Amendment regulatory requirements, initially using a conservative approach of multiplying the worst-case soil gas concentration by the operating flow of the system to derive an emission in mass per unit time. More information about this topic can be found in:

- Air Emissions from the Treatment of Soils Contaminated with Petroleum Fuels and Other Substances EPA/600/SR-97/116 November 1997 http://www.p2pays.org/ref/07/06430.pdf. Also previous full text version is EPA-600/R-92-124, July 1992.
- In the National Emission Standards for Hazardous Air Pollutants for Site Remediation http://www.epa.gov/ttn/atw/siterm/fr08oc03.pdf.

4.4 Structural and Occupancy Aspects for New and Existing Buildings

Relevant characteristics of building types for VI mitigation include:

- Size
- Air exchange rate (AER)/methods
- Types of construction
- Economic and effective life span of the building
- Daily and/or seasonal occupation patterns
- Other sources of related indoor air pollutants
- Exhaust Ventilation, and
- Current and reasonably anticipated future use.

Results of a detailed building survey covering these factors must be considered in design. Input should be solicited from all interested stakeholders (including tenants) and feedback received should be incorporated into the design process. For instance, mitigation has a direct impact on residential homeowners and they are accordingly concerned about numerous issues such as potential diminution of real estate value, aesthetics and health risk. On-site design activities, installation, operation and maintenance will need to accommodate homeowners individual schedules and needs.

Designers of vapor intrusion mitigation systems should consider all forms of ventilation of the structure—those provided by heating and cooling systems, operational practices such as window and door opening, and exhaust ventilation. Design of a new structure provides an opportunity to integrate mitigation of vapor intrusion into the selection of heating and cooling systems, which are normally driven based on energy economics, aesthetics/preference and custom. For example, a system design that avoids creating negative pressures inside the structure and/or maintains positive pressure inside the structure should be preferred and is required in some jurisdictions.

Vapor intrusion mitigation of existing buildings is most common, but installation of mitigation systems and barriers is easiest and cheapest during new construction. Both situations are encountered in practice. Older structures are less likely to have adequate vapor barriers incorporated into the foundation construction and the foundation itself is more likely to have developed cracks (NHDES, 2006).

4.4.1 New Buildings

Siting of new construction can be one of the most powerful means to control vapor intrusion potential in reuse and revitalization (e.g., brownfields). For example, contaminated areas most likely to produce vapor intrusion in a reuse scenario may be set aside for green space. If land adjacent to an affected building is covered, such as parking lots, the resultant direction of migration of the vapors should be considered so as to not impact adjacent structures. In construction of slabs for new buildings, a monolithic pour is preferred to a slab floating on a foundation, because it eliminates the expansion joint, that can often be an entry pathway. Site-specific factors that should be evaluated when selecting a remedy for existing structures include the depth and seasonal variability of the water table, the vadose zone soil type and permeability and frost depth (EPA, 1993a).

One frequently-recommended remedy for new buildings involves the installation of a passive sub-slab VOC collection and vent piping (that can be converted to an active system later if necessary), and a membrane system underneath the foundation. Alternately, new buildings may be designed to include a highly ventilated, low-occupancy area underneath, such as a parking garage. All considerations for the existing structure retrofit remedies described above are applicable for installation of membrane and passive venting in new construction with the following changes: If an appropriately permeable engineered layer of material (e.g., gravel or drainage mat) is used beneath the slab, evaluation of native soil characteristics may be less critical or unnecessary.

According to California's guidance, gas barrier/membrane systems in new construction should meet the following requirements:

- Gas resistant membranes should be constructed of appropriate materials and thicknesses for the situation and contaminant of interest.
- Gas resistant membranes should be placed a maximum of one foot below the foundation slab and a maximum of six inches above the gas collection piping.
- Protective layers consisting of at least two inches or more of sand and/or geotextile (six ounces per square yard at a minimum) should be laid below and above the membrane. The term "geotextile" refers here to a woven or nonwoven fabric used in civil engineering, usually synthetic.
- Without an engineering evaluation and confirmation data to support the beneath footing passage, the membrane should not pass below footings and/or stiffener beams of slabs due to seismic concerns. Membranes should be sealed carefully where they encounter footings or stiffener beams.
- Gas tight seals (e.g., boots) should be provided at all pipe or conduit penetrations through the membrane and where the membrane attaches to interior and perimeter footings.
- A leak test of the membrane system (such as a smoke test) should be conducted to ensure no leaks exist. Where leaks are identified, appropriate repairs should be undertaken and smoke testing should be repeated until no leaks are detected. (DTSC, 2004)

In some situations, newly constructed buildings will require active subsurface venting to alleviate vapor intrusion. An air permit from the local regulatory authority is sometimes required for an active venting system. Additional design considerations for an actively vented building include:

- Active injection of air under a building to enhance venting is not recommended without an engineering design. The air injection system may force vapors into a building by creating elevated subsurface pressures or force vapors into unprotected neighboring structures. Permitting requirements may apply to these systems in some jurisdictions.
- For sites where subsurface concentrations are above the lower explosive limit (LEL) of any contaminant/vapor the site should be carefully evaluated. A deep well pressure relief system or other improvements, which reduce or eliminate subsurface gas levels and pressures, should be considered in addition to the building protection system (DTSC, 2004).

A more detailed discussion of approaches that can be used in new construction is presented in EPA (1993a), pages 2-38 to 2-45.

Many provisions of model building codes that are intended to ensure drainage or provide waterproofing may also offer some benefit in vapor intrusion mitigation when properly applied. The selections below are from the international building code (IBC) while the international residential code (IRC) is similar, see http://www.iccsafe.org/ for full text.

IBC § 1806.1: Damp-proofing and Waterproofing/ Where Required. Walls that retain earth and enclose interior spaces and floors below grade must be waterproofed or damp-proofed. (Damp-proofing is the application of coatings or other materials in order to prevent the passage of water under slight hydrostatic pressure; waterproofing is required to prevent the passage of water or water vapor under significant pressure.)

IBC § 1806.2.1: Damp-proofing Required/Floors. Damp-proofing materials must be installed between the floor and the base course (gravel), unless a separate floor is installed above the concrete slab, in which case the damp proofing can be applied above the concrete slab. Where applied below the slab, damp proofing should consist of 6-mil polyethylene or other approved material; above the slab, 4-mil polyethylene is acceptable. (This prevents moisture from entering belowground spaces. Rigid insulation would be preferable.)

IBC § 1806.3.3: Waterproofing Required/Joints and Penetrations. Joints in walls and floors, joints between the wall and floor, and penetrations of the wall and floor must be made watertight (to ensure the effectiveness of waterproofing, and prevent water from entering the building or becoming trapped in the foundation walls or floor slab).

IBC § 1806.4.1: Floor Base Course. Floors of basements must be placed over a floor base course at least 4 inches thick consisting of gravel or crushed stone. (The gravel or stone provides a capillary break so that moisture from the soil below will not rise to the underside of the floor. It can also act as a drainage system for water under the slab.)

IBC § 1911.1: Minimum Slab Provisions/General. Floor slabs placed directly on the ground must be at least 3½ inches thick. A polyethylene vapor retarder or other approved material must be placed between the base course or sub grade and the concrete floor slab.

4.4.2 Existing Buildings

The existing structure and foundation type usually dictate the type of mitigation system needed. For each different foundation and structure type, attention should be paid to the likely entry pathways of vapor intrusion and how the pathways may indicate certain remedies as discussed in section 3. Qualitative discussion of the effect of foundation type on vapor intrusion potential is found in ASTM (2005) section X2.3.2.2(d). In many cases existing foundation features can be modified cost effectively to provide vapor intrusion mitigation. For example, perimeter drainage systems can be adapted in some cases to provide depressurization or ventilation under the slab. A crawlspace may be isolated from the living space by sealing and ventilated to reduce concentrations in the crawlspace. Foundation wall cavities may also be ventilated to reduce vapor intrusion (EPA, 1993a).

4.4.2.1 Basements and Slabs on Grade

About 43 percent of U.S. single unit houses (that are not mobile homes) have at least partial basements and 30 percent are on slabs (HUD, 2006). In these structures the composition of the sub-slab region should be determined during a survey before system design. The presence, composition, or absence of sub-slab aggregate/ drainage layers, the presence or absence of moisture barriers, and the porosity of fill materials can strongly influence the potential for success of sub-slab depressurization systems (EPA, 1993a).

Basements generally have more surface area in contact with the soil providing more intimate interaction and consequently more opportunities for entry pathways. Any cracks in the slab or openings around utility penetrations offer potential pathways. Also, the expansion joint between the slab and the foundation or basement wall is a major potential entry route. Contaminated soil gas can also migrate into the cores of a block wall to enter either through openings at the top of the wall or through the pores in the blocks. In some cases, depressurization systems may be required in the block cores, as well as under the slab.

For a slab-on-grade building, entry routes through the slab are similar to those of basement slabs, except that construction details of the contact between the slab and foundation may be different. Some slabs are floating on top of a foundation, leaving an expansion joint between the slab and wall. Other slabs are poured continuously over top of the entire foundation wall and thus do not need an expansion joint. In conjunction with the sealing of potential subsurface vapor entry points, an active SSD system can effectively be used in buildings with a basement slab or slab-on-grade foundation.

Earthen floors and field stone foundations are more porous and provide increased opportunity for vapor intrusion. (NHDES, 2006) For buildings with dirt floor basements, either an SSD system with a newly poured slab or a sub-membrane depressurization system with a soil vapor barrier may be used. Traffic on the membrane and use of the area would need to be limited in an SMD application. The SSD method is preferred in the NY guidance (NYSDOH, 2005). SSD allows more effective use of the space but would be more expensive to construct.

4.4.2.2 Masonry Foundation/Crawlspace

About 26 percent of U.S. single unit housing (excluding mobile homes) has a crawlspace (HUD 2006). Ventilation of crawlspaces is effective primarily when only modest VI reductions are required. In cold climates ventilation frequently results in freezing the plumbing lines. For crawlspaces with concrete slabs, SSD systems work well. SMD systems also work well in the event of no slab. If the air handler and the return ducts of the heating and cooling (HAC) system are located in the crawlspace, crawlspace contaminants may be transported into the living space through the supply ducts. The ducts are prone to leak and the return side of the system has very large negative pressures, which can draw crawlspace air with contaminants into the ducts and pump them to the living space through the supply ducts.

New York State's guidance calls for sub-membrane depressurization to be used in enclosed crawlspaces (NYSDOH, 2005). This is consistent with Henschel's (1992) review of methods for radon mitigation specific to crawlspaces. EPA (1993b) section 8 has extensive information on sub-membrane depressurization applications to crawlspaces. Additional information can be found in ASTM's "Specification for Plastic Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs" (ASTM, 1993).

Conditioned crawlspace with concrete slabs have been recently recommended for energy and moisture reasons (Lstiburek 2004), but these systems may be problematic where vapor intrusion occurs because they encourage air movement from the crawlspace into the occupied portion of the structure. They also rely on passive sealing to prevent soil gas entry into the crawlspace. An SSD system would be a recommended addition when VI is suspected and a conditioned crawlspace is selected.

4.4.2.3 Mobile Homes

Relatively little testing of mobile homes for vapor intrusion and few mitigation actions for them have been published. However, since mobile homes constitute eight percent of the of the U.S. housing stock and 15 percent of new housing constructed they must be considered (HUD, 2002). Mobile homes without skirts (and thus with good circulation of ambient air under the floor) should have a lower risk of vapor intrusion than structures in which the floor is in direct contact with the ground. Provisionally, it is reasonable to treat mobile homes with well-sealed skirts as being similar to crawlspace structures. In mobile homes it is always prudent to understand where heating and HVAC intake and returns are located. Anthropogenically induced or exacerbated vapor intrusion problems may exist if intakes or returns are located in the skirts of mobile homes. The same applies for crawlspaces. Some mobile homes are placed on concrete slabs. In these cases mitigation strategies used in frame structures placed on slabs are probably appropriate. An extensive discussion of mobile home vapor intrusion is presented on pages C2 and C3 of ITRC 2007.

4.5 Cost Factors

When there are two or more feasible technologies for mitigation of vapor intrusion, cost will obviously influence the selection. When the vapor intrusion is occurring in multiple structures, the costs will rise, although economies of scale may allay the additional expenses. A quantitative analysis of the costs associated with acquiring, installing, monitoring, operating, and maintaining different vapor intrusion technologies is highly site specific and will not be attempted in this paper. Some cost analysis information for vapor intrusion mitigation options has been presented in Welt and Thatcher (2007) and reprinted as part of Table 1 of this document. Costs for various types of active soil depressurization systems as applied for radon reduction were published by Henschel (1991). Unit costs for many elements that may go into mitigation systems are systematically surveyed and cataloged in the RS Means manuals, along with adjustment factors for costs in various locations. These costs are updated annually, however it is important to note that the costs are based on large commercial, industrial, multi-family housing projects and may need to be adjusted when applied to small projects. The user should also refer to the general instructions on estimating costs provided in the introduction to each volume and chapter of these manuals (www.rsmeans.com). The manuals provide detailed information for individual unit price items as well as summarized information for typical assemblies. For example:

- The RS Means manual on "Building Construction Data" includes detailed data for such topics as various types of foundations, sub-slab drainage systems, waterproofing membranes, joint sealers and caulks.
- The RS Means manual on mechanical cost data covers drainage, dewatering, foundations, joint sealers, caulking, flashings, chimneys/stacks, HVAC systems, energy recovery equipment, ducts, ventilators, air-cleaning devices etc. Costs for assemblies such as ventilation systems are also provided.

When estimating costs for vapor intrusion mitigation one should be aware that many solutions to vapor intrusion also have multiple benefits. For example, dewatering/drainage systems that may already be planned may be adaptable for vapor intrusion. Sealing may provide energy cost savings as well as vapor intrusion mitigation.

In many cases, active and passive systems are similar in capital cost, but active systems usually have higher operating, maintenance and energy costs. Mitigation technologies are likely to affect energy consumption in the building. Certain components of the technologies such as fans for active depressurization systems or air cleaners, are energy users themselves, but they are also likely to have an effect on the energy economy of the building. Typical active residential systems have a operating and energy cost impact on the order of $300/year. Other technologies such as sealing or the installation of membranes are likely to provide modest energy cost benefit. Extensive cost analysis is reported for various radon mitigation systems in Henschel 1991 and EPA 1993b chapter 13. A source for extensive further information is http://www.energysavers.gov/ which includes sections tailored for the specific needs of homeowners, contractors and builders, and building managers. Numerous software tools used to evaluate energy efficiency and economics are reviewed and cataloged at http://www.eere.energy.gov/buildings/tools_directory/, including those specific to indoor air quality and ventilation/airflow.

4.6 Risk Communication and Stakeholder Involvement Considerations

Because vapor intrusion mitigation systems directly address an ongoing or potential human exposure, clear and timely risk communication with stakeholders is vital. The general topic of risk communication and stakeholder involvement is too extensive to be addressed in this engineering issue paper. Good information can be found at:

- http://www.epa.gov/oswer/riskassessment/risk_communication.htm;
- http://www.epa.gov/superfund/community/pdfs/37riskcom.pdf
- http://www.epa.gov/superfund/community/cag/pdfs/ci_handbook.pdf
- State documents such as: Chapter 11 of the NJDEP Vapor Intrusion Guidance Document (NJDEP, 2005) and section 5 of the Draft NY Guidance (NYDOH 2005)

A few specific stakeholder communication recommendations for vapor intrusion mitigation projects can be made:

- Mitigators should remember that a "person's home is his/her castle." Most people have a strong emotional attachment to their home and neighborhood, so any concern or need expressed by a homeowner should be treated with sincerity and understanding
- Environmental workers should provide stakeholders with an understanding of the problem at the onset. A written letter or notice that describes both the problem and the steps that could or will be taken to address the problem can make face-to-face negotiation with homeowners easier. Project staff should then schedule a time to meet with the stakeholder to discuss how you intend to assess and solve the problem. Note: it is always best to not downplay any requirements imposed on the stakeholder /homeowner in advance, because any subsequent modifications that require less of the homeowner's time or use of the home or building will usually be interpreted in favor of mitigation. However, any additional burden not conveyed initially could likely be interpreted

with a degree of suspicion, as a failure to understand the problem and its solution. In short, the homeowner's faith in the mitigation contractor's expertise is important for accomplishing the job correctly and on time.

- Stakeholders will likely be interested not only in risk reduction, but also in the maintenance of property resale value, aesthetics, system noise, system maintainability and energy cost impacts. Environmental professionals should be prepared to address these issues when meeting with homeowners, tenants or building owners.
- When making technology selections, environmental professionals should consider how intuitively understandable the technology will be to a resident or occupant without a background in environmental science. For example, the concepts of membrane barriers and sealing should be readily understandable. HVAC modifications or sub-slab ventilation systems may require more careful explanation.
- Environmental workers should provide written materials explaining system operation and maintenance issues, which can be used for ongoing reference and even conveyed from one owner/tenant to future tenants/owners. If a given system will result in an increase in cost (e.g., electricity), be prepared to provide justification and an estimate for the cost.

Further recommendations in this area are found in Appendix A of ITRC 2007.

5 VERIFICATION OF MITIGATION PERFORMANCE

After a technology is selected, designed and installed, its performance must be verified before and during long term operation (see Figure 3 for a graphical portrayal of the process).

5.1 Defining the Performance Objective

As was discussed in the previous section, prior to installing a mitigation system, the project team must formulate a clear overview of the problem to be solved. The team must know why the mitigation project will be done—and have common pertinent background information for decision making. As in any environmental project, a quality assurance project plan (QAPP) process, including the development of data quality objectives (DQO),

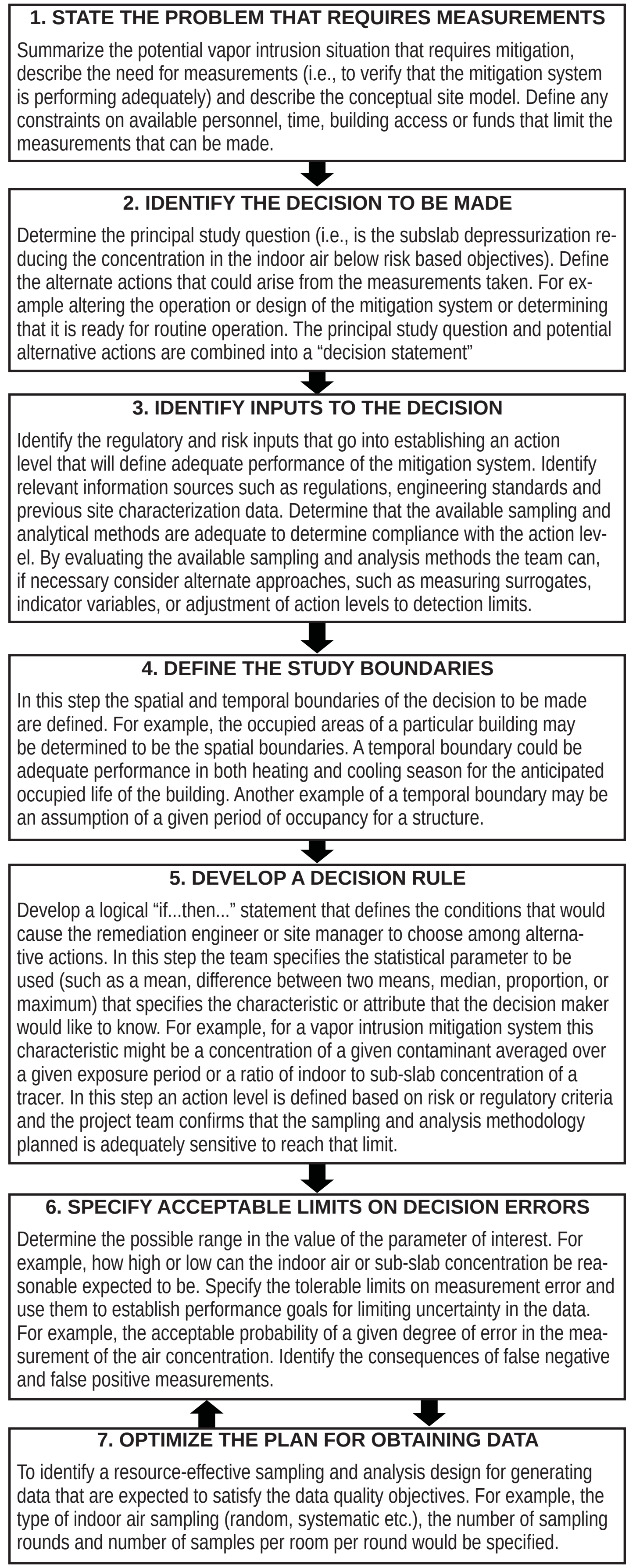


Figure 8. Data quality objective process. (Modified from EPA, 2000)

should be used to clearly define project objectives both qualitatively and quantitatively. For cost efficiency, these QAPPs are usually developed and applied on a site-wide basis. The development and documentation of clear objectives ensures that all involved understand and agree on the underlying purpose of the project. The development of clear objectives increases the likelihood that the system design will address and accomplish that purpose and that the measurements taken will be able to verify that the purpose has been achieved (EPA, 2002b).

EPA recommends a formal seven step DQO process (EPA, 2000) illustrated in Figure 8 whenever environmental data are being gathered for decision making http://www.epa.gov/quality/qa_docs.html. In the case of an engineered mitigation system the problem (step 1) is to control the vapor intrusion exposure pathway or to remove the source of the vapors. The decision (step 2) might typically be to determine whether the mitigation system was operating as designed and/or was sufficiently protective to yield an indoor environment that does not lead to unacceptable exposures. Many of the inputs (step 3), boundaries (step 4) and decision rules (step 5) will flow easily from information developed during the initial investigation and risk assessment of the vapor intrusion issue (see section 2.1 and EPA, 2002a). The primary decision rule (step 5) would focus on whether the indoor air concentration had been reduced below a risk based standard with a given certainty and a given system reliability (percent time in operation). Secondary decision rules might be established based on engineering parameters of the system, such as maintenance of a given negative pressure in a sub-slab ventilation system, continuous operation and/or a specified flow rate, etc.

According to EPA (2000), "Setting tolerable limits on decision errors (step 6) is neither obvious nor easy. It requires the planning team to weigh the relative effects of threat to human health and the environment, expenditure of resources, and consequences of an incorrect decision, as well as the less tangible effects of credibility, sociopolitical cost, and feasibility of outcome. In the initial phases of the DQO development, these probabilities need only be approximated to explore options in sampling design and resource allocation." For example it would be necessary to define the acceptable probability of deciding on the basis of measurements that the mitigation system was operating correctly (and in a protective manner) when in fact it was not and some unacceptable level of exposure/risk or hazard remained.

In defining your statistical basis for decision (step 5) and limits on acceptable error (step 6) several important factors should be acknowledged:

- The risks posed by a given vapor intrusion situation should be classified as either potentially acute or chronic. An example of an acute hazard is exposure to a toxic VOC at levels that exceed 'Immediately Dangerous to Life and Health' (IDLH) levels set by National Institute for Occupational Safety and Health (NIOSH) for industrial settings or the acute minimal risk level (MRL) set by the Agency for Toxic Substances and Disease Registry (ATSDR) in residential or educational settings. These values can be found at http://www.cdc.gov/niosh/idlh/intridl4.html and http://www.atsdr.cdc.gov/mrls/index.html. Chronic risks arise from long-term exposure to lower concentrations of toxic chemicals. Another example of an acute hazard would be the presence of methane at a concentration approaching its lower explosive limit (LEL). The necessary system reliability (and thus engineering redundancy) for a vapor intrusion problem posing an acute risk would be much higher than for an exposure posing only a chronic risk. Remedies for acute risks also must be implemented more quickly. Because acute risk levels are often far above chronic levels, situations with concentrations exceeding an acute level will likely require a highly effective technology be selected to achieve several orders of magnitude reduction. The issue of exposure duration is thoroughly discussed in the Indiana draft guidance [Indiana Department of Environmental Management (IDEM, 2006)].
- The expected length of system operation, frequency of monitoring and number of building occupants influences the development of a decision rule and the tolerable decision error for a chronic risk.
- Ambient air concentrations in urban areas, as well as typical indoor air concentrations, frequently exceed conservative screening values used in many vapor intrusion evaluations. Most vapor intrusion mitigation systems will not provide air quality better than ambient air outside the home.

Although these issues are critical, the remainder of the section 5 of the engineering issue paper will address in detail step 7: methods used for obtaining data about whether the mitigation system is functioning effectively.

5.2 Defining the Performance Baseline

The primary performance metric for a vapor intrusion mitigation system is the achievement of acceptable levels of contaminants in indoor air. Additionally, engineers may wish to determine percent reduction in measured contaminant(s) concentrations in indoor air resulting from the engineered system or barrier. Secondary indicators of performance may include engineering parameters such as pressure differentials and AER.

Several factors influence the premitigation performance baseline to which system performance is compared, and thus should be held constant to the extent possible in system performance measurements:

- Vapor intrusion is expected to be seasonally and temporally variable (influenced by weather) at most sites. Therefore, multiple measurements over several seasons or sets of meteorological conditions may be needed to accurately define the baseline. On the other hand, it may not be acceptable from a risk perspective to delay installation of a mitigation system for many months in order to obtain multiple baseline measurements. This is one reason why systems and/or barriers should be designed conservatively.
- Vapor intrusion measurements can be easily complicated by the presence of sources of the same pollutants within the structure (this is often referred to as vapor intrusion "background"). These sources can include, for example, consumer products and hobby materials, process emissions in an industrial setting and emissions from both cooking and vehicles in many types of structures. If these conditions change independently of the VI source it may complicate interpretation of indoor air concentration measurements before and after mitigation. Sub-slab soil gas measurement can help determine whether vapor intrusion makes a significant contribution to indoor levels of contaminants especially in the cases where one contribution is dominant over the other. In many cases an independent tracer for sub-slab soil gas can be a useful tool for distinguishing vapor intrusion.
- AER and pressures in a structure can be significantly altered by such simple everyday actions as turning on or off an HVAC system or opening a window. Pressure differences across the building shell can in turn be affected by changes in wind load, temperature and exterior barometric pressure.
- Exposure to pollutants stemming from vapor intrusion depends on the location within the structure. For example exposures may differ by factors of two or three depending on floor or proximity to ventilation sources. Variability is likely to be higher in structures without HVAC systems.

A detailed discussion of meteorological factors, sample locations, etc., is provided in:

- Chapters 4 and 5 of The Commonwealth of Massachusetts, Indoor Air Sampling and Evaluation Guide (MADEP 2002)
- Chapter 2 of the NY State draft guidance (NYDOH 2005) http://www.health.state.ny.us/nysdoh/gas/svi_guidance/docs/svi_main.pdf

However, to ensure that a system is protective for chronic exposure, measurement conditions must either:

- Represent the worst case indoor air concentration (conservative) or
- Be taken at multiple times sufficient to adequately describe the variation in the indoor air concentration and thus estimate the long term average exposure (30 or 70 year exposure periods are used for most risk assessment calculations).

5.3 Methods of Measuring Indoor Contaminants

Sampling the indoor air for COC is the most direct way to determine if exposure has been addressed at a site where vapor intrusion is suspected. Measurements of indoor air quality along with ambient and/or sub-slab soil gas sampling could also be used to more directly assess the performance of the mitigation system. Keep in mind that evaluation of VI risk reductions from indoor air will often be complicated by the presence and variations in background COC from both outdoor (ambient) and indoor sources. In addition, spatial and temporal distributions of contaminants in indoor air can depend, to a large extent, on the locations of the indoor sources, and the nature of their uses. For instance, the frequency of opening and closing containers of cleaners, solvents, paints and adhesives is a source of variation. Thus the interpretation of VI is complex when multiple significant sources (e.g., VI, indoor and ambient) are present. The subjects of representative indoor air sampling and background sources have thus been discussed widely in nearly every vapor intrusion investigation document (both state and federal) and other literature.

In addition to vapor intrusion, indoor sources can contribute to degradation of indoor air quality. Thus, mitigation-related sampling programs should include updates to indoor air quality surveys (including chemical inventories) if any changes have occurred since the characterization phase. Concurrent sampling of ambient air, indoor air, and sub-slab vapors is preferable, both for quality control and for comparisons to determine if contaminants are likely to be attributable to vapor intrusion rather than ambient or indoor sources.

5.3.1 Indoor Air Sampling for Contaminants

In buildings, COC may not be distributed uniformly in space and time. Thus, the sampling plan must carefully consider the locations, number and frequency of samples. Sample placement (usually breathing zone) and duration (usually 24 hours, but depends on facility use) are frequently selected to meet risk-assessment-related requirements. Durations of 24 hours are typically used to average over the diurnal cycle. Ideally a period that is a large multiple of 24 hours would be used to allow for variations to occur on longer than a diurnal cycle. The air within relatively open zones (such as auditoriums, reception areas, and living spaces of residential buildings) that have nearly uniform temperatures can be reasonably expected to have contaminants well mixed within the zone. Measured variations within such zones are often comparable to the observed variations of duplicate measurements. Short term spatial variations are usually small compared to temporal variations on daily and seasonal scales. Strong drafts, strong temperature gradients, or flow restrictions may be sufficient cause to question whether the zone is well mixed. When a complex building is being evaluated, it is typical to represent it by a conceptual model consisting of a group of interacting zones. It is often necessary to treat different floors of a building as separate zones. It is also common practice to consider parts of a building with separate air handler systems as independent zones. Special attention should be applied to QA/QC considerations (especially sampling and analysis) in the very low concentration environment of the indoors (EPA, 2002).

The strategy for designing an indoor-air sampling program depends very much on the intended use of the results. An evaluation of health risks needs long-term estimates of concentrations that can be applied to an exposure scenario. For this purpose the building should be operated in its normal manner.

Diagnostic measurements for studying a particular entry mechanism or for evaluating the effect of a mitigation system on a particular entry mechanism may require different building operation protocols. Most measurements used for diagnostic purposes impose constraints on the building that contribute to those purposes. Frequently, investigations will attempt to minimize the short term variation in indoor concentrations in order to obtain more reproducible results. Often these procedures involve maintaining the building in a closed condition (windows and doors closed), which usually tends to maximize the indoor concentrations. Some would argue this yields a conservative value of concentration for risk estimates, which may be the case if the measurements are performed during the season of highest indoor concentration. Using a consistent set of constraints on the building has the advantage that data sets can be more readily compared from season to season and from one study to another.

Detailed advice for planning and implementing an indoor air sampling program is given in a number of documents, including MADEP, 2002 and DTSC, 2005. In most cases, the HVAC system should be operated for at least 24 hours before confirmation sampling to maintain a normal indoor temperature. Windows should be closed while such samples are collected.

The most commonly used sampling methods are EPA Methods TO-14A and 15, which require use of a stainless steel canister and TO-17, which uses sorbent tubes. New Jersey and Massachusetts guidance (NJDEP, 2005 and MADEP 2002) provides a comprehensive discussion of the use and QA/QC requirements for each method.

ASTM (2005) recommends an initial sampling round(s) for COC shortly after start-up of the mitigation system; then, when sufficient reductions have been demonstrated, reducing the monitoring frequency to "every couple of years." They also recommend including winter sampling in the long term monitoring program.

5.3.2 Measurements of AER and Soil Gas Entry Rate

The air exchange rate (AER) can be measured using either tracer gases (ASTM Method E741) or by the blower door method (ASTM methods E779 or E1827).

When using a tracer gas one may use a constant emission rate source in which the AER is computed from the measured steady state concentration of the tracer and the known emission rate of the source. In an alternate tracer approach one injects a puff of a tracer gas and then monitors its rate of decay with time. The effective rate of decay is then called the AER. Soil gas entry rates can also be directly measured by monitoring a second tracer unique to the soil gas (such as radon). A unique tracer could also be injected into a sub-slab gravel layer or permeable mat. Any soil gas constituent that is known not to have indoor or ambient sources can serve as a surrogate for soil gas entry.

When the AER is measured under a positive pressure scenario with frequent monitoring of individual contaminant concentration(s) in indoor air over time, soil gas and indoor sources can be distinguished. If, under positive pressure, the contaminants do not decay to non-detectable levels, an indoor or ambient source is indicated. Using the measured AER and the measured ambient concentration, the effective emission rate of the indoor source can be determined. Then from a mass balance analysis a soil gas entry rate can be calculated. For more information on tracer methods of AER measurements please see:

- ASTM E741 E741-00 Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution
- Dietz and Cote, 1982

5.4 Measuring or Estimating Sub-slab Soil Gas Concentrations During Mitigation

5.4.1 Sub-slab Measurements

During mitigation, sub-slab measurements are not always required but if performed, may be used for several purposes. If the sub-slab concentration substantially decreases that is a strong sign that an SSD or SSV system is working. However, a failure to decrease the concentration is not necessarily an indication that the system is not working. An SSD system can work even if it does not reduce sub-slab concentration because it reverses the pressure differential.

Sub-slab probes can also be used to monitor differential pressures for a direct indication of the performance of sub-slab depressurization or SVE systems.

5.4.2 Sub-slab Sampling Procedures

Sub-slab samples can be collected from beneath slab-on-grade or basement slabs. A sub-slab sampling approach is typically useful only if the water table is sufficiently below the slab to allow a soil gas sample to be collected. If the seasonal high water table and capillary water reach the foundation, the entry processes are likely to be altered for some period of time (NJDEP, 2005).

The sub-slab sampling plan should be based on:

- Knowledge of the building's footing and slab design (footings can sometimes subdivide the subsurface area beneath the building, potentially creating a "trapping zone" for vapors),
- The location of utility corridors (both because they influence the contaminant distribution and for safety),
- Knowledge of the dominant entry points to the structure, if possible, as well as the source location/expected routes of contaminant migration.

It is difficult to state general rules as to where in the building footprint points should be placed or how many are required. However, if there are multiple occupied spaces that differ in ways likely to influence air exchange with the sub-slab space (i.e., floor/sub-floor materials, HVAC system in use, etc) samples from each space will be needed.

Detailed instructions for installation of sub-slab sampling probes are provided in several documents (e.g., DiGiulio, et al., 2005, NYSDOH, 2005; NJDEP, 2005; and MADEP, 2002). Sub-slab sampling probes may be temporary or permanent. A small-diameter hole is made through the slab and into the sub-slab fill material. The probe is installed through the slab and must be well sealed into the slab to prevent leakage between the probe and the slab.

The HVAC system should be operated for at least 24 hours before sampling to maintain a normal indoor temperature. Advice on sample collection from sub-slab probes is provided in various documents (DiGuilio et al., 2005; DTSC, 2005; NYSDOH, 2005; NJDEP, 2005). These and other documents provide further information on analytical methods, QA/QC procedures and supplemental data collection (e.g., building surveys, soil characterization) essential to a sub-slab sampling program.

Generally, multiple rounds of testing are advised to assess variability of sub-slab concentrations due to diurnal and seasonal effects, HVAC operation, changes in source strength, vapor migration, and occupant activities (NYSDOH, 2005; ASTM, 2005), if the variability is not well understood prior to mitigation. Diurnal and seasonal effects are caused by temperature, wind, and barometric pressure variations as well occupant activities and HVAC operational changes. Usually diurnal patterns are less noticeable in the sub-slab concentration than in the indoor concentration.

5.5 Indirect Measurements of Mitigation Performance

The measurements described in this section are not definitive measures of performance but are commonly used to evaluate the mechanical operation and influence on the sub-slab zone of a mitigation system. They do provide useful secondary indicators in some circumstances.

5.5.1 Tracer and Smoke Testing

Tracers can be used either to measure the AER in the structure, which is discussed above in section 5.3.2 or for leak detection through barriers or building materials as discussed below. Tracers could also be used to find leaks in HVAC systems or in SSD ducts.

Smoke testing is a qualitative form of tracer testing used to detect leaks or preferential vapor migration pathways, or to test airflow patterns. A smoke stick or smoke tube which generates a stream of visible smoke can be used to test for leakage through seams such as pipe joints and slab-wall junctures (EPA, 1993). Leak testing of pipe joints is more effective when the smoke is injected into the pipe under positive pressure. Testing after the pipe assembly is complete is more definitive than smoke testing during assembly. However, testing during assembly is a recommended quality control step. Timing of smoke testing for membrane construction applications is discussed in section 3.3.4. New York guidance (NYSDOH, 2005) recommends the use of smoke tubes to test for leaks at seams and seals of membranes in sub-membrane depressurization systems; at cracks and joints in the concrete slab, as well as at the suction point in sealed sub-slab depressurization systems; and at potential leakage points through floors above sealed crawlspace systems.

A limitation of smoke testing in existing structures is that non-noxious smokes are expensive and cheap high volume smoke sources can leave undesirable residues. The efficacy of smoke testing in some applications has been questioned on the grounds that many leaks are too small for visual detection using this method (Maupins and Hitchins 1998, Rydock, 2001), and that leaks large enough to detect using smoke could be detected in other ways. More quantitative methods have been recommended, such as tracer testing and using instrumentation for quantitative results.

5.5.2 Communication Test of Sub-slab Depressurization

Communication tests, or pressure field extension tests, are commonly used in the design of sub-slab depressurization systems to ensure that the engineered sub-slab depressurization field extends under the entire slab and foundation. A set of diagnostic tests referred to as sub-slab communication and pressure field extension tests are fully described in several documents (ASTM E2121-03, EPA 1993b, Fowler, et al., 1990). These documents describe not only how to use the results of the diagnostic tests to select a mitigation method, but also how to design and install the system. Good communication or pressure field extension is necessary for effective SSD. The absence of sub-slab depressurization suggests a higher potential for contaminant entry. For purposes of designing a sub-slab depressurization system, the test is conducted by applying suction at a drill hole in a central portion of the slab and observing the pressure difference across the slab at holes drilled in other locations. Locations for pressure measurements should extend to the extremes of the slab. A micromanometer should be used to measure pressure differentials at measurement points (NYSDOH, 2005). If the pressure field extension cannot be quantified with a micromanometer the performance of the mitigation system may be in question. A pressure difference that causes smoke to move in the desired direction, but is not measurable on a micromanometer probably indicates an insufficient margin of safety. The same sub-slab measurement probes could be used both to measure the design diagnostics and for performance testing after the system is installed. A lack of pressure differential could indicate moist soils near the slab that limit air permeability, a footing that separates test points, or other flow issues. The potential performance of an SSD system may be judged on its ability to extend an adequate pressure field under the entire slab. Section 4.3.3 of ITRC (2007) presents a detailed discussion of the pros and cons of conducting communication tests before design vs. installing a standard system and then testing it/adjusting it after installation.

5.5.3 Pressure Differential Testing

For designed pressurization systems or HVACs that rely on differential pressure to prevent advective flow of soil gases into the building, the mechanical performance should be verified by measuring the pressure differentials across the slab. This measurement is typically accomplished with micromanometers or electronic pressure meters. While the pressure differential between the indoors and ambient at ground level may serve as an acceptable surrogate, it is the pressure differential across the slab that prevents soil gas entry. For basements, the walls that are underground become part of the critical building envelope that must prevent soil gas entry.

5.6 Initial and Long-Term Verification of System Performance

After installation, the system performance must be verified. Such initial acceptance testing should include verification of the mechanical performance of the system combined with appropriate air concentration measurements. Initial verification might use an existing tracer such as radon to demonstrate its reduction in the indoor air.

Monitoring approaches, at least in the early stages, should include direct measurement of the concentration of VOCs in indoor air and possibly pressure differentials in the sub-slab soil gas. Monitoring programs may also include measurement of factors known to control vapor intrusion such as pressure differentials, AER or the achievement of complete negative pressure field extension for a sub-slab depressurization system.

As part of initial system operation testing, fireplaces, woodstoves, or other combustion or vented appliances must be checked for possible backdrafting which could introduce dangerous combustion gases, especially carbon monoxide (CO), into the structure (NYSDOH, 2005). Longer-term periodic monitoring may consist of inspections of equipment, materials and surrounding conditions, physical measurements, leak testing, other testing or sampling (ASTM, 2005; NYSDOH, 2005). Completion of any needed maintenance should follow from the results of periodic monitoring. Based on monitoring results, system performance should be critically evaluated to determine whether modifications or replacement are warranted (ASTM, 2005).

If indoor air sampling for COC is included in the periodic monitoring plan, sampling events during the heating season should be included. When assessing system performance at new construction sites, monitoring of volatile organics should take into account the initial off-gassing of new building materials, furniture, etc. (NYSDOH, 2005)

When mitigation systems are not operating effectively, diagnostic testing can be used to identify design or installation problems and suggest ways to improve the system. A detailed discussion of such diagnostic testing is presented on pages 5-5 to 5-10 of EPA 1993a.

Termination of the system may be requested once it can be demonstrated that the vapor intrusion pathway is no longer complete. New Jersey requires termination sampling of indoor and sub-slab air (NJDEP, 2005). Section 4.5 of ITRC (2007) provides a detailed discussion of steps for regulatory closure of vapor intrusion mitigation systems, including considerations for multiple building sites. The stakeholders may, however, recognize additional benefits of the mitigation system that could justify the continued operation of the system after the hazard from the contaminant of initial primary concern is remediated. For example systems can reduce moisture leading to reduced mold, mildew and musty odors indoors. Systems also provide protection against intrusion of naturally occurring radon gas.

5.6.1 Operation and Monitoring (O&M) Requirements for SSD/SSV Systems

ASTM (ASTM, 2005) calls for regular monitoring and maintenance intervals and makes useful suggestions for how to select a monitoring interval (sections 6.3.8 and 8). The average lifetime of the devices should be taken into account. For example, ASTM states: “The monitoring frequency will be a function of the timeframe for possible failure of the engineering control (i.e., more frequent for an active system, less frequent for a passive system) and the relative effect of such a failure on a potential receptor (more frequent for immediate impact, less frequent for a delayed impact). Design specifications may include (1) a monitoring frequency that varies over the operating period of the engineering control or (2) a provision to evaluate and modify the monitoring frequency based on data or information obtained during monitoring and maintenance." For example, it may be acceptable to reduce sampling frequency once performance objectives for indoor air quality are met (preferably during the heating season). Likewise, decreased inspection /maintenance frequency may be acceptable once efficient system operation has been demonstrated for a year (NJDEP, 2005). ASTM also suggests triggers for unscheduled inspections such as floods, earthquakes, building modifications, etc.

Typical O&M activities for the mitigation of vapor intrusion by either passive or active venting/depressurization systems may include the following (from DTSC, 2004 and NYSDOH, 2005):

- All newly mitigated buildings should be given an initial indoor air test to determine if the mitigation remedies are operating and performing according to design specifications. For both active and passive depressurization systems this testing should include tests of the pressure field extension to the extremities of the slab. Manometers or suitable pressure gauges will be required to test the pressure field extension.
- Routine inspection of the area of concern, including all visible components of the mitigation system and collection points, should be performed to ensure there are no significant changes in site condition and there are no signs of degradation of the mitigation system.
- Routine monitoring of vent risers for flow rates and pressures generated by the fan should be conducted to confirm the system is working and moisture is draining correctly.
- Routine maintenance, calibration, and testing of functioning components of the VOC venting systems should be performed in accordance with the manufacturers' specifications.
- Periodic monitoring of air on the lowest accessible floor and enclosed areas of the building and grade surface areas is needed to ensure there are no significant increases in subsurface gas concentrations.
- Periodic verification of adequate pressure differentials (min 5 Pa) across the slab should be done.

Additional information on operation and maintenance of venting systems may be found in Chapter 4 of NYSDOH (2005).

5.7 The Role of Ongoing Warning Devices and System Labeling

According to ASTM (2003a): "All active radon mitigation systems shall include a mechanism to monitor system performance (air flow or pressure) and provide a visual or audible indication of system degradation and failure." This advice should be equally applicable to vapor intrusion systems for other contaminants. ASTM goes on to say "The mechanism shall be simple to read or interpret and be located where it is easily seen or heard. The monitoring device shall be capable of having its calibration quickly verified on site."

The Wisconsin guidance provides a detailed discussion of what circumstances and for what contaminants odor can provide a warning of the existence of vapor intrusion problems (pages 7–9)
http://dhfs.wisconsin.gov/eh/Air/pdf/VI_guide.pdf.

Fixed gas detectors have been widely employed for such acutely hazardous air pollutants as CO and methane in residential and industrial applications. Fixed detectors using infrared (IR) or photoionization (PID) devices are also available for volatile organics (Skinner and Avenell, 2005). Government websites that provide information about the selection and installation of gas detectors of various types include:

- http://www.nidcd.nih.gov/health/smelltaste/gasdtctr.asp
- http://www.osha.gov/dts/ctc/gas_detec_instruments/index.html
- http://www.lbl.gov/ehs/pub3000/CH13A.html
- http://www.msha.gov/TECHSUPP/ACC/lists/22methne.pdf

The New York and New Jersey vapor intrusion documents also recommend durable pressure monitoring devices and/or alarms (NYSDOH, 2005; NJDEP, 2005). Such devices may indicate operational parameters (such as on/off or pressure indicators) or hazardous gas buildup (such as percent LEL indicators). System failure warning devices or alarms should be installed on the active mitigation systems (for depressurization systems), and appropriate responses to them should be understood by building occupants. Monitoring devices and alarms should be placed in readily visible, frequently trafficked locations within the structure. The proper operation of warning devices should be confirmed on installation and monitored regularly.

Permanent placards should be placed on the system to describe its purpose, operational requirements and what to do if the system does not operate as designed (e.g., phone number to call). These placards should be placed close to the monitoring/alarm part of the system as well as close to the fan or other active parts of the system. The placard should also tell the building occupant how to read and interpret the monitoring instruments or warning devices provided.

6 ACRONYMS AND ABBREVIATIONS

AER	Air Exchange Rate
AFB	Air Force Base
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COC	Contaminant of Concern
COPC	Contaminants of Potential Concern
DCE	Dichloroethene
DQO	Data Quality Objectives
EPA	Environmental Protection Agency
EPDM	Ethylene Propylene Diene Monomer
HAC	Heating and Cooling
HAP	Hazardous Air Pollutants
HDPE	High Density Polyethylene
HVAC	Heating Ventilation and Air Conditioning
IBC	International Building Code
IDEM	Indiana Department of Environmental Management
IDLH	Immediately Dangerous to Life and Health
IR	Infrared
IRC	International Residential Code
ITRC	Interstate Technology and Regulatory Council
LDPE	Low Density Polyethylene
LEL	Lower Explosive Limit
MACT	Maximum Achievable Control Technology
MRL	Minimal Risk Level
NESHAP	National Emission Standards for Hazardous Air Pollutants
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrogen Dioxide
O&M	Operation and Monitoring
OSC	On Scene Coordinator
PID	Photoionization Detector
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RPM	Remedial Project Manager
SMD	Submembrane Depressurization System
SSD	Sub-slab Depressurization
SSP	Sub-slab Pressurization
SSV	Sub-slab Ventilation
SVE	Soil Vapor Extraction
TCE	Trichloroethene
TPY	Tons per Year
USGS	United States Geological Survey
UV	Ultraviolet
VI	Vapor Intrusion
VDPE	Very low density polyethylene
VOC	Volatile Organic Compounds

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This Issue Paper was intended as an overview on vapor intrusion mitigation for EPA staff, regional program of-

fices, RPM's and State governmental environmental staff. Because vapor intrusion is a rapidly evolving environmental phenomenon, interested parties should further consult the body of literature and experience that constitutes the state-of-the-art of vapor intrusion and vapor intrusion mitigation. As of the date of this publication, questions may be addressed to Mr. Mosley, EPA ORD NRMRL (mosley.ronald@epa.gov; 919/541-7865) and/or Mr. Cody, EPA Region I (cody.ray@epa.gov; 617/918-1366).

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