# SUMMARY OF RESEARCH ON MITIGATION SYSTEM DESIGN AND MONITORING

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## Abstract

The U.S. DOD sponsored research through the ESTCP Program for improved understanding of mitigation systems for radon and volatile organic compounds under project number ER2013-22. This presentation summarizes the findings of the 5-year study. For large buildings, the research indicates that significant improvements in cost-effectiveness can be achieved using a few new lines of evidence and a spreadsheet model. Lines of evidence include steady vacuum versus radial distance from a suction point, transient vacuum measurements (change in vacuum vs time in response to turning the fan on or off) and fitting data to equations to calculate the transmissivity (T) of the material below the floor slab and the leakance (B) of the floor slab. Helium tracer testing to measure flow rates below the slab and mass removal rate monitoring provide added value for system design and monitoring.

## Introduction

Subsurface vapor intrusion (VI) to indoor air of VOCs and radon pose potential health risks to building occupants through inhalation exposures. The most common method for mitigating risks is subslab depressurization (SSD), which is also known as active soil depressurization (ASD) or may be referred to as subslab ventilation (SSV) if the goal is to reduce concentrations below the floor slab instead of establishing a vacuum below the floor. These mitigation systems extract gas from below the floor slab of the building and discharge to outdoor air. Design and performance specifications were developed by radon researchers decades ago and were based mostly on achieving a measurable vacuum below the concrete floor slab. For example, U.S. EPA, (1988) recommended a minimum applied vacuum of 4 pascals and ASTM (2013) recommended a minimum applied vacuum of 6 to 9 pascals. Revisions to guidance documents are in progress at the time of this report (ANSI/AARST RMS-LB, RMS-MF, RMS-SF for large buildings, multi-family residences and single-family residences, respectively). This poses an opportunity for advances to design and performance assessment. The objective of this research was to develop a more comprehensive approach to provide protective systems at a lower overall cost.

## Experimental Methods

This research was predicated on the conceptualization that an SSD/SSV or ASD system is essentially a “capture system” that could be designed and monitored using methods analogous to those used to contain the migration of a plume of contaminated groundwater (Bear, 1979).

[1] *This work was funded by the Environmental Security Technology Certification Program (ESTCP) and in-kind contributions from Geosyntec Consultants, Inc.*

Pneumatic testing similar to a soil vapor extraction system pilot test is used for data collection, as described by McAlary et al., 2010 and 2018. The vacuum versus time data are fit to the Hantush-Jacob (1955) Non-Steady Leaky Aquifer Model (Equation 1) to calculate T and B values (Masman 1989, Thrupp et al., 1996 and 1998).

**Equation 1.** Vacuum as a function of time

$$Vacuum\ (t) = \frac{Q_{SSV}}{4\pi T} \int_{y=U}^{\infty} exp\left(-y - \frac{r^2}{4B^2 y}\right) \frac{\partial y}{y}$$

Where y is a variable of integration and U and B are defined as:

**Equation 2.** Well Function.

$$U = \frac{r^2 S}{4Tt}$$

**Equation 3.** Leakance of the floor slab.

$$B = \sqrt{\frac{K\ b\ b\prime}{K\prime}}$$

and: T = transmissivity of the region below the floor slab [$L^2/T$] (T=Kb)
U = well function [dimensionless]
B = leakance [L],
$Q_{SSV}$ = discharge from the extraction well [$L^3/T$]
r = radial distance from extraction well (L),
π = 3.14159
t = time since the start of gas extraction [T]
S = storativity [dimensionless]
K = pneumatic conductivity of the zone of extraction [L/T] which is equal to the transmissivity divided by the thickness,
b = thickness of the zone of extraction [L],
b' = thickness of the floor slab [L],
K' = bulk average vertical pneumatic conductivity of the floor slab [L/T].

The vacuum versus distance data are then fit using Equation 4:

**Equation 4.** Vacuum as a function of radius.

$$Vacuum\ (r) = \frac{Q_{SSV}}{2\pi T} K_0\left(\frac{r}{B}\right)$$

where:
$K_o$ = Modified Bessel function of the second kind of order zero of (r/B) [unitless].
Some iteration may be required to obtain calibration of both Equation 1 to the vacuum versus time data and Equation 4 to the vacuum versus distance data using one unique pair of T and B values, however; there are two variables (T and B) and two lines of independent sets of data (vacuum versus time and vacuum versus distance), which is generally sufficient to yield a unique

solution. The calibrated T and B values can then be used to calculate velocity versus radial distance using **Equation 5.** Velocity as a function of radius.

$$Velocity\ (r) = \frac{Q_{SSV}}{2\pi bnB} K_1 \left(\frac{r}{B}\right)$$

where: *n* = air-filled porosity of the zone of extraction [volume of air/volume of soil]; and
$K_1$ = Modified Bessel Function of First Order of (r/B) [unitless]

Travel time from a given distance can be determined by integrating the velocities over discrete segments of the distance using:

**Equation 6.** Travel time as a function of radius.

$$t_{travel} = \int \frac{\partial r}{v(r)}$$

where: *vI* = velocity at a given radial distance [L/T]
$t_{travel}$ = travel time from a given radial distance I [T]

The calculated travel times can be compared to subslab tracer test data to provide another independent method of calibrating the model inputs and evaluating how well the system behavior matches the behavior predicted by the model. Two types of tracer tests were developed in this research: the inter-well tracer test (a small volume of helium is injected into a subslab probe and the arrival is monitored in the suction pipe), and the helium flood (the system flow is reversed, helium is added at about 1%v/v and the arrival of helium is monitored at subslab probes at various distances).

The air-filled porosity (n) can usually be estimated with reasonable accuracy, so this parameter is not particularly sensitive. The thickness of the permeable layer (b) can often be assessed by visual inspection of soil core, but otherwise, the helium tracer tests provide an independent line of evidence for verification of the b value.

The calibrated model can also be used to calculate the relative proportion of the total gas flow extracted that originates below the slab (QI) as a proportion of the total extracted gas flow (Qssv) using Equation 7:

**Equation 7.** Relative proportion of flow originating from below the floor slab.

$$Q(r)/Q_{SSV} = \frac{r}{B} K_1(r/B)$$

where $K_1$ is the first order Bessel Function. Equation 7 can be used to calculate the level of dilution of the subslab vapor concentrations caused by indoor air leakage across the floor slab for various distance from the point of suction I. Equation 7 can also be used to calculate the amount of conditioned indoor air that is drawn across the slab, which can be used to assess whether and to what extent there is value in sealing floor cracks, seams, joints and utility penetrations. Equations 2 through 7 are easily solved using a spreadsheet.

Equations 4, 5, 6 and 7 provide a means to calculate radial profiles of vacuum, velocity, travel time and leakage across the floor slab. This raises the question of what values for each parameter would likely be protective. Criteria for each of these lines of evidence will likely evolve as time progresses and empirical evidence is gathered, but for the time being, there are reasons to propose the following (see ESTCP ER-2013-22 Final Report for details):

- Vacuum – compare to site-specific cross slab differential pressure, measured over time using a pressure transducer and data logger
- Velocity – achieve a target velocity of about 3 ft/day or more imposed by the system
- Travel time – achieve a travel time of about 0.1 day or less from all areas with subslab vapor or radon concentrations of potential concern
- Leakage across floor slab – consider floor sealing when the leakage across the floor slab approaches a significant proportion of the ambient building ventilation rate

The rate of mass removal by the system also provides a useful performance metric that can be compared to the mass loading through a building via building pressure cycling as a means of demonstrating the adequacy of the mitigation system design and performance. It can also be used to support an exit strategy if the system is clearly capturing all the available mass and the rate of mass removal of the mitigation system is insufficient to pose an indoor air quality concern considering the building size and air exchange rate. The mass flux can be conceptualized using a mass balance equation:

**Equation 8.** Mass balance approach to calculate mass flux of a SSV system and building mass flux.

$$-D_{eff}\ (\delta C/\delta z)\ A = Q_{SSV}\ C_{SSV} + Q_{build}\ C_{IA}$$

where:

| | |
|---|---|
| $D_{eff}$ | effective diffusion coefficient for the compound of interest [$L^2$/t] |
| $\delta C/\delta z$ | vertical concentration gradient [mass/length$^2$ or M/$L^2$] |
| A | building footprint area [$L^2$] |
| $Q_{SSV}$ | subslab venting system flow rate [$L^3$/t] |
| $C_{SSV}$ | subslab venting system concentration [M/$L^3$] |
| $Q_{build}$ | building ventilation rate [$L^3$/t] |
| $C_{IA}$ | concentration in indoor air [M/$L^3$] from vapor intrusion (i.e. assumes no background indoor air contributions) |

The goal of the SSV/SSD system is to keep $C_{IA}$ below a threshold. If the SSD system effectively captures all the available mass flux, then $C_{IA}$ is reduced to zero and Equation 8 reduces to:

**Equation 9.** Mass flux equation reduced assuming the indoor air concentration is required to be zero

$$-D_{eff}\ (\delta C/\delta z)\ A = Q_{SSV}\ C_{SSV}$$

The upward diffusive flux of VOC vapors on the left side of Equation 9 is typically the rate-limiting step once mass in storage has been removed, so it can essentially be considered a threshold or target mass flux (MF) for the SSV system to contain, in which case Equation 9 reduces to:

**Equation 10.** Mass flux equation reduced to assume a target value for SSV capture.

$$MF = Q_{SSV} C_{SSV}$$

The goal of optimizing the SSV system is to select a $Q_{SSV}$ that will maintain a mass removal rate (the product of $Q_{SSV}$ x $C_{SSV}$) equal to MF as determined by: 1) $D_{eff}$ ($\delta C/\delta z$) A, estimated from vertical profiles of sampling and analysis and soil property data, or; 2) $Q_{build}$ $C_{IA}$, estimated from building pressure cycling. The mass removal rate from the system will initially include removal of mass from storage and subsequently stabilize at a level controlled by the upward diffusive flux. If the area of influence of the SSV system extends beyond the boundaries of the building, the mass removal rate may exceed the target mass flux by some margin. In the optimized system, the subslab vacuum may be low enough that occasional fluctuations in the building pressure could cause small amounts of soil vapor flow into the building. This is inconsequential if the upward flow is short-lived and the air entering the building was simply indoor air that moments earlier flowed in the opposite direction, or if the subslab ventilation rate is sufficient to reduce subslab concentrations to levels low enough to contribute negligible mass to the building over the duration of the pressure field reversal.

The mass flux also can be used to estimate a reasonable maximum indoor air exposure concentration ($C_{buildRME}$) that would be expected to be sustained if there was no operating SSV/SSD system:

**Equation 11.** Using mass flux to calculate the maximum indoor air exposure concentration

$$C_{buildRME} = MF/Q_{build}$$

$Q_{build}$ can be measured directly (ASTM, 2017 or ASTM, 2012) or estimated from the literature. The U.S. EPA's Exposure Factors Handbook (U.S. EPA, 2011) lists the mean air exchange rates as 1.5 AE/hr for commercial buildings and 0.45 AE/hr for domestic residences, which can be multiplied by the length, width and height of the building to estimate $Q_{build}$.

By similar logic, a mass flux screening level (MFSL) can be calculated with Equation 12, which represents a threshold MF below which vapor intrusion is unlikely to pose an unacceptable health risk. This can be useful for defining an exit strategy if the available mass flux is or becomes insufficient to sustain indoor air concentrations above a threshold risk.

**Equation 12.** Mass flux screening level to estimate an unacceptable health risk.

$$MFSL = IASL \times Q_{build}$$

where:

IASL = indoor air screening level $[M/L^3]$

## Results

Examples of each line of evidence are shown as follows:

- ambient cross-slab differential pressure (ΔP) to establish building-specific target subslab vacuum levels, see Figure (1);
- subslab vacuum vs time in response to fan cycles (on/off) as shown in Figure (2) and subslab vacuum vs radial distance as shown in Figure (3) for matching to Equations 1 and 4 to characterize the transmissivity (T) and leakance (B);
- subslab tracer testing as shown in Figure (4) to measure travel time from different radial distances to the point of suction to enable performance evaluation based on travel time and velocity;

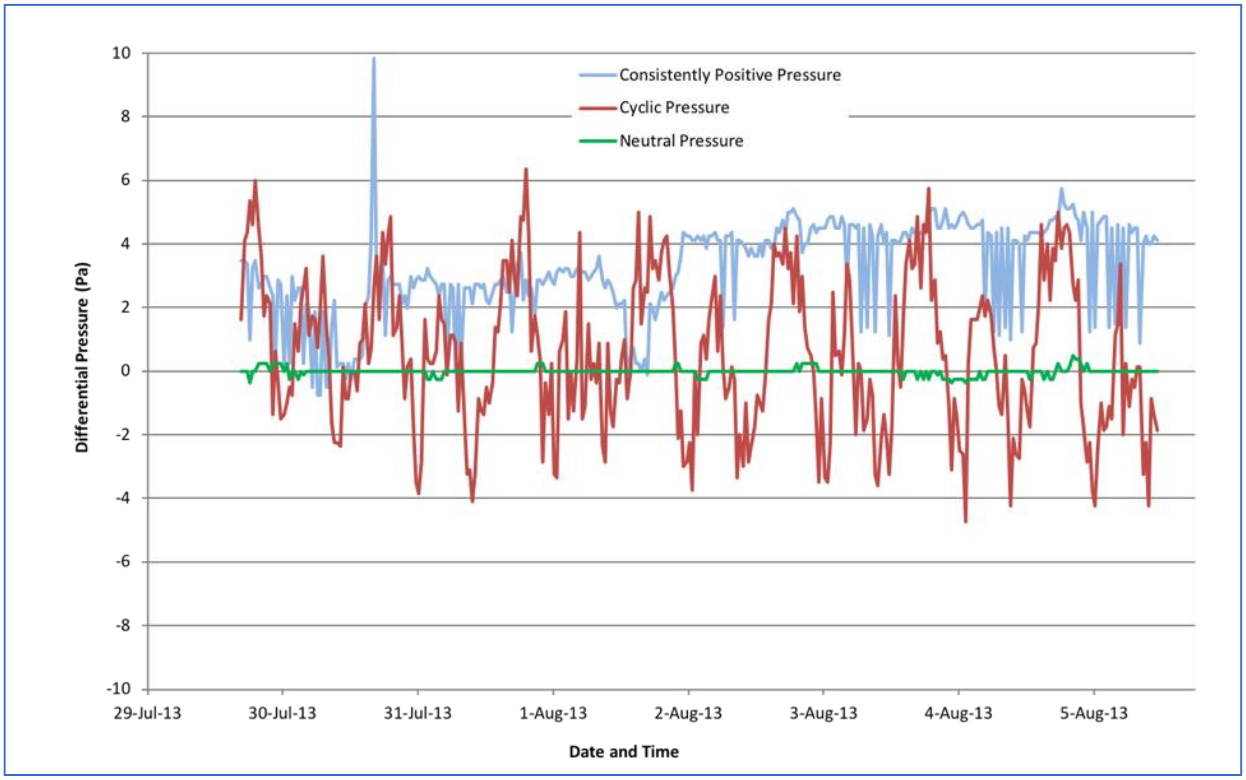
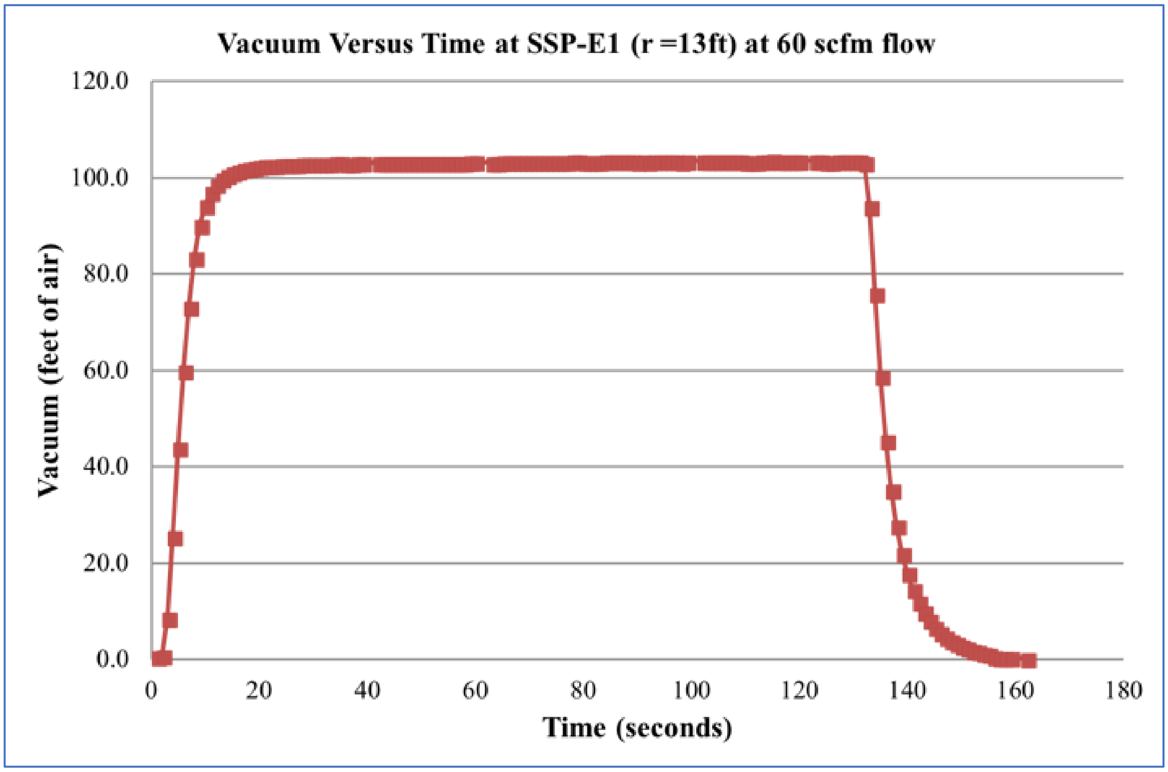



Figure (1): Example of cross-slab differential pressure for three buildings with no SSV systems



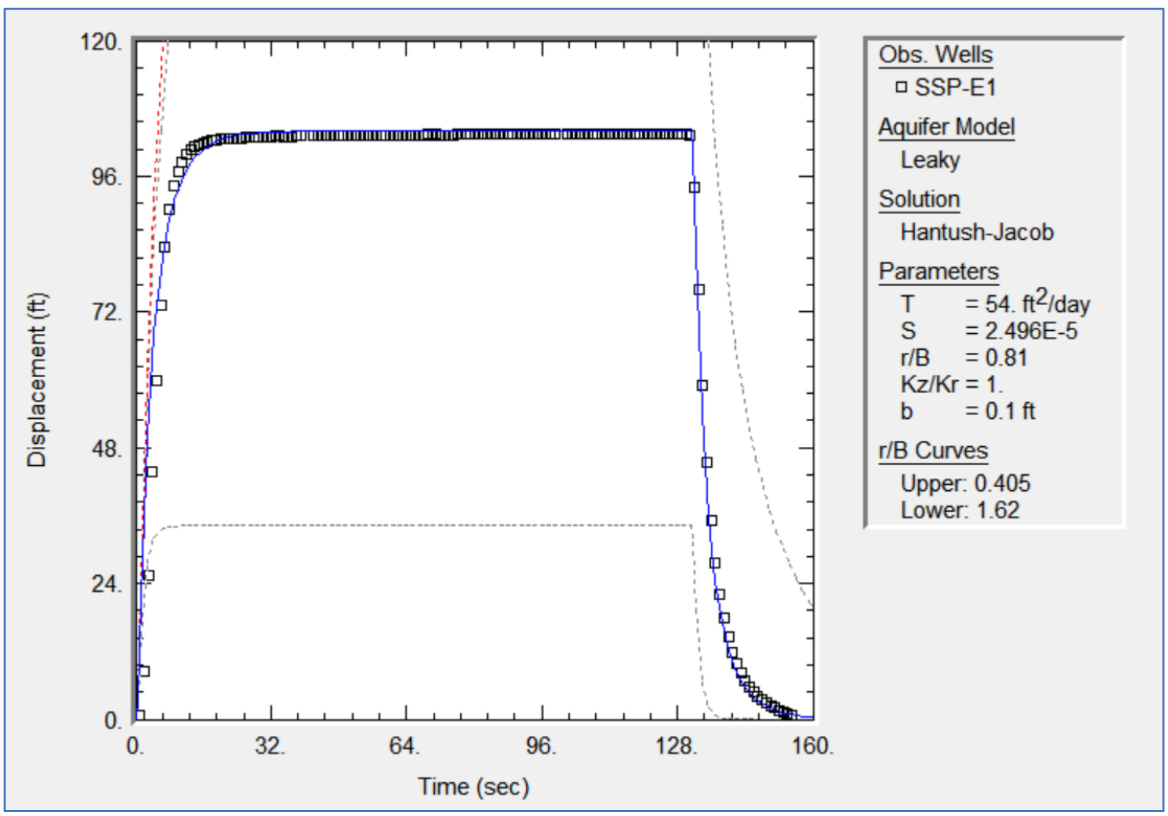




Figure (2): Example of subslab vacuum vs time: raw data (top), and fit to the Hantush-Jacob Model (bottom), using AQTESOLV, by HydroSOLVE, Inc. of Reston, VA

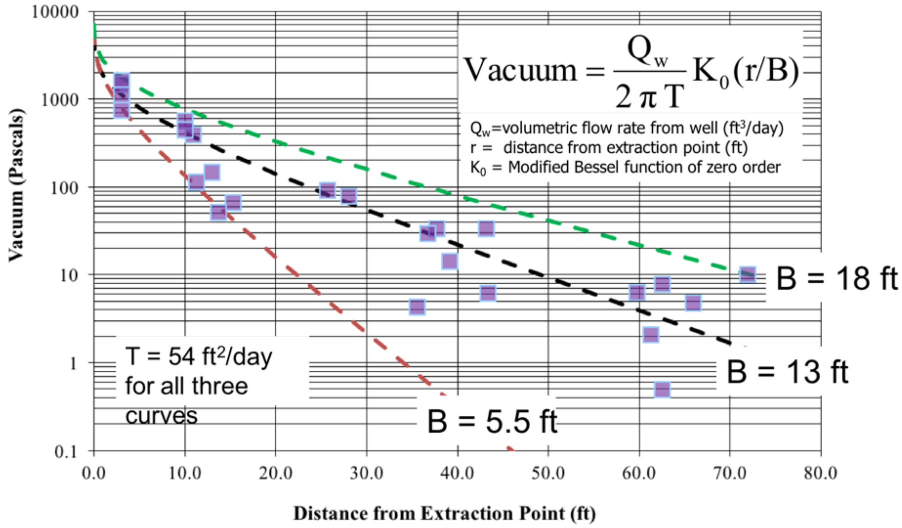
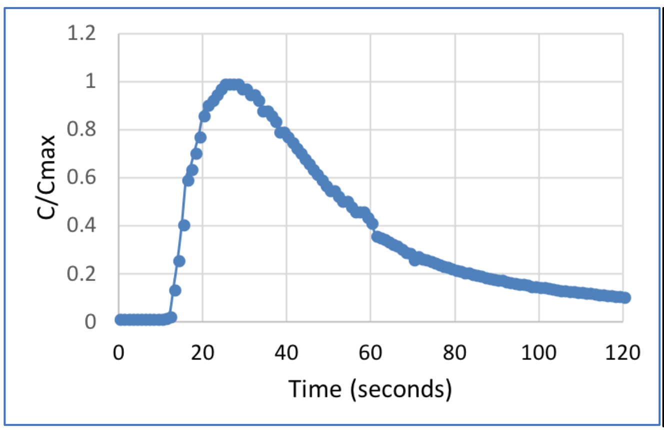



Figure (3): Comparison of vacuum vs distance measurements to profiles calculated using the Hantush-Jacob Model



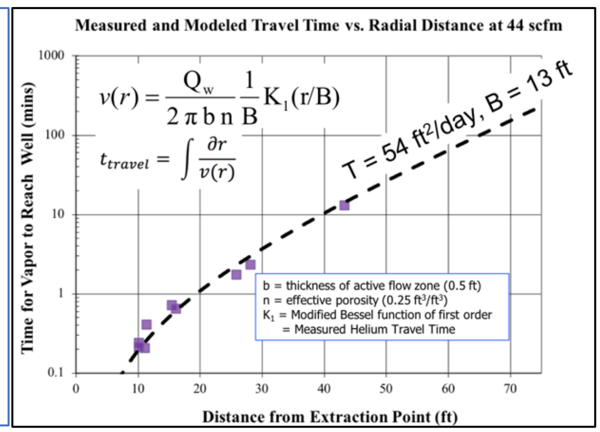




Figure (4): Measured (left) and modelled (right) travel time vs distance from suction point

Analysis of these data yields information regarding the temporal distribution of ambient cross-slab pressure differential, the transmissivity of the material below the floor, the leakage of the floor, the thickness and effective porosity of the dominant zone of air flow beneath the floor, the radial profiles of vacuum, travel time, gas velocity and proportion of flow originating below vs above the floor as shown in Figure (5), which provide lines of evidence for system design and performance assessment.  These data can also be used to calculate a building-specific attenuation factor (AF) to support customized subslab screening levels:

**Equation 13.** Calculation of attenuation factor based on pneumatic properties of the subslab materials and building.

$$AF = \frac{T\,\Delta P}{B^2 h\ AER}$$

where T, ΔP and B are defined above, h is the height of the building (ft) and AER is the air exchange rate (air exchanges per day) (McAlary et al., 2018).

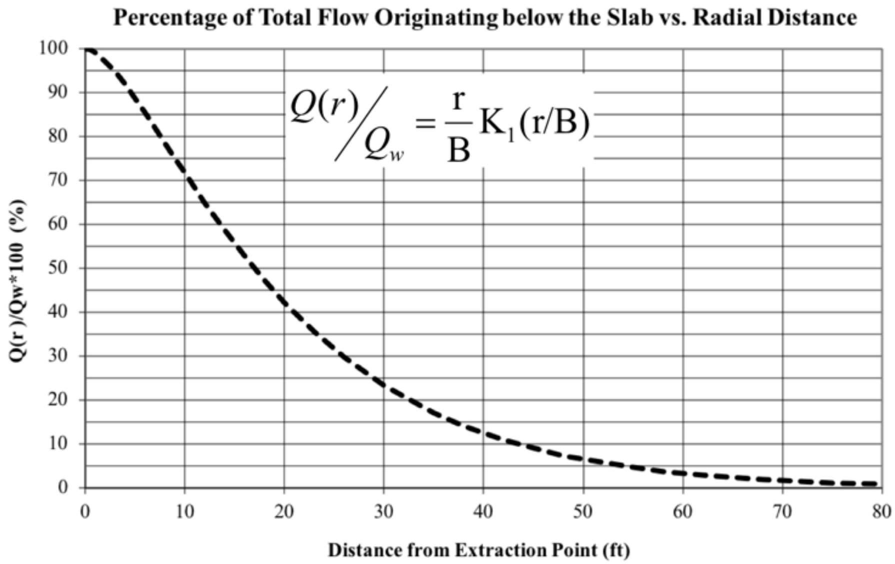



Figure (5): Proportion of flow originating below the floor vs radial distance

## Discussion

Figure (6) provides a summary of the technology and how it can be integrated with conventional mitigation system design and performance monitoring practice. The left side of Figure (6) summarizes current standard practice. The additional lines of evidence developed in this research are outlined in the middle (recommended) and right (optional). For simple cases, the conventional approach may be sufficient. For example, in a single-family dwelling with a reasonably competent floor slab and moderate to highly permeable granular fill, the additional recommended and optional lines of evidence may not be needed to develop a cost-effective mitigation system. For cases where the conventional approach results in ambiguous results, additional lines of evidence are very helpful. For example, if the system has a high flow rate, but there is no measurable vacuum at the distal communication test points, subslab tracer testing can quickly demonstrate whether there is rapid flow (indicating that the absence of a measurable vacuum is simply attributable to a very high transmissivity) or not (indicating that the extracted gas may be short-circuiting through a preferential pathway).

The incremental costs of many of these lines of evidence are very low. For example, the inter-well tracer tests and transient vacuum monitoring typically takes only a few minutes with equipment that is commonly used by field technicians familiar with vapor intrusion assessment and mitigation. Additional assessment effort becomes increasingly cost effective as the total cost of the mitigation system increases, which is typically a function of the size of the building. So, in general, it will be appropriate to employ more of the recommended and optional activities in larger buildings, compared to single family residences.

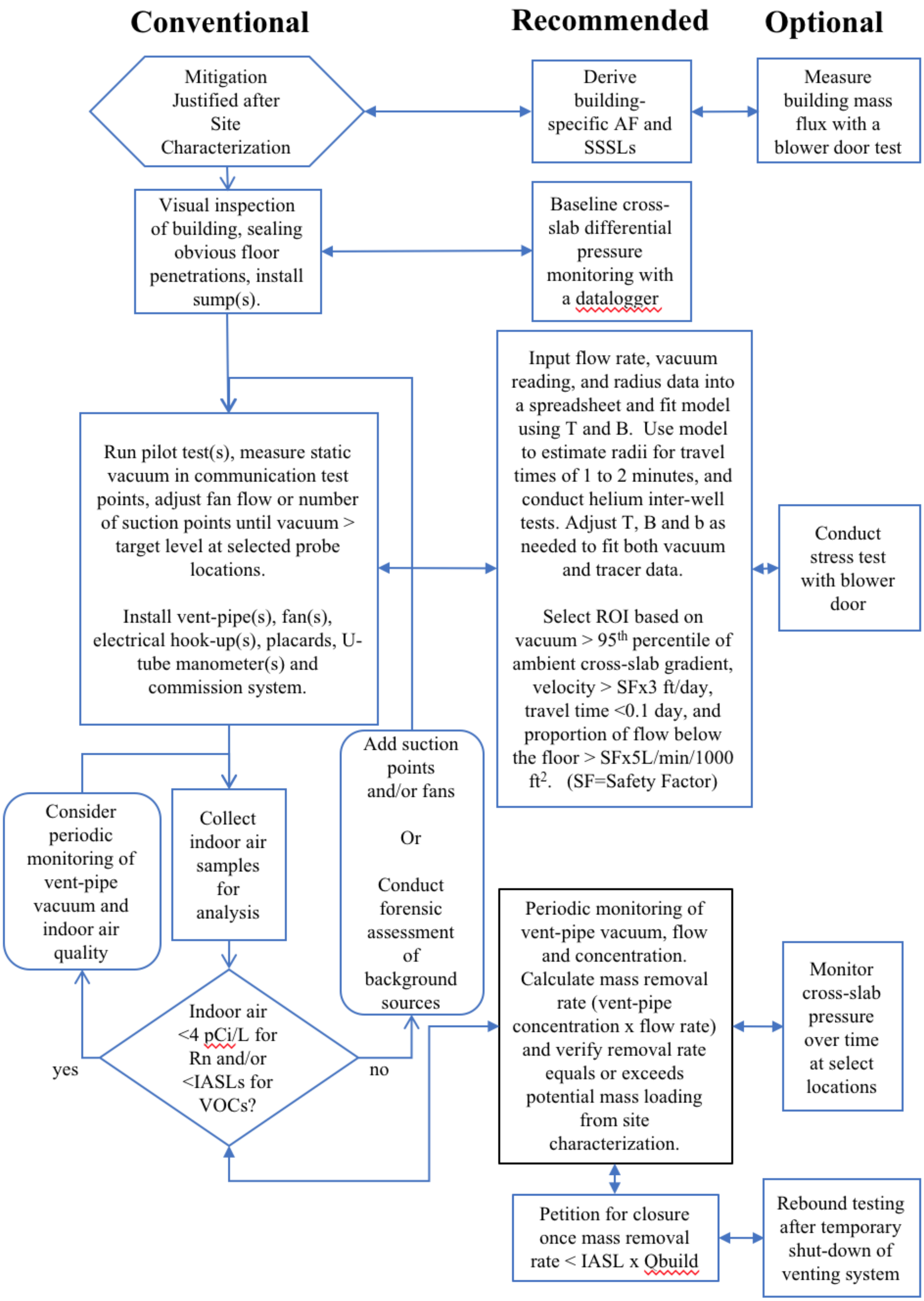



Figure (6): Logic flow diagram for mitigation system design and performance monitoring.

Where the material below the floor is granular fill (which is usually specified in building codes) and the floor is relatively competent (e.g., few utility penetrations, epoxy sealants, sealed expansion joints), the spacing between suction points can be very large, which reduces the capital cost of installation for a large building. If the material below the floor is highly permeable, the flow velocity and induced ventilation below the slab can be sufficient to reduce subslab concentrations by SSV, even in areas where the induced vacuum is too small to reliably measure. If the ventilation rate below the slab is sufficient to reduce the VOC and radon concentrations to very low levels, then an occasional reversal of the cross-slab pressure gradient will not result in substantial subslab VOC transport into the building. In such cases, current standard practice generally results in unnecessary installation of larger fans and more suction points, which both increases capital and operation costs, but also results in wasted energy because conditioned indoor air is extracted and exhausted outdoors. Energy efficiency is a growing concern in the design of SSD and SSV systems (Moorman, 2009).

Where the material below the floor has a low permeability and the subslab vapor concentrations are very high (i.e., >~1E6 $\mu g/m^3$), diffusive transport of VOCs through the floor slab can potentially pose indoor air quality concerns even if there is an appreciable vacuum below the floor and supplemental measures such as increased building ventilation or carbon filtration may be needed as interim measures until there is a reduction in subslab vapor concentrations.

## Summary

The aim of the research was to develop new lines of evidence for the design and performance monitoring of subslab venting systems to mitigate human health risks attributable to subsurface vapor intrusion to indoor air for volatile organic compounds (VOCs) and radon. Several new lines of evidence were developed and demonstrated at four test buildings, ranging in size from 2,200 $ft^2$ to 64,000 $ft^2$. Measurements include vacuum vs distance, vacuum vs time, subslab tracer testing and ambient differential pressure monitoring. Mathematical modeling is calibrated to the transmissivity below the floor slab, the leakance of the floor or other preferential pathways, and used to predict trends of vacuum, velocity, travel time and leakance for comparison to newly proposed decision criteria. The new methods provide insight that has previously not been available, and can reduce the costs of mitigation considerably for large buildings with slab-on-grade construction and granular fill below the slab, which is a very common building design.

The new lines of evidence developed in this research are relatively fast and simple with readily-available equipment and the mathematical models are commercially available or readily programmed into a spreadsheet. As a result, the costs to implement are modest compared to the potential savings in capital and operations, maintenance and monitoring. Net savings are expected to be larger for larger buildings. The testing program demonstrated that conventional methods for determining a radius of influence may result in a much greater number of suction points being installed than are really needed, which is costly and disruptive. Total system flow rates may commonly also be overdesigned, which wastes electricity to run the fans and also incurs excess energy costs when conditioned indoor air is drawn through the floor and wasted by discharge to outdoor air.

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