# ESTCP
# Executive Summary

(ER-201322)

# Demonstration/Validation of More Cost-Effective Methods for Mitigating Radon and VOC Subsurface Vapor Intrusion to Indoor Air

July 2018

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ESTCP
ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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**14. ABSTRACT**

New lines of evidence and mathematical modeling are developed to aid in the design and performance monitoring of subslab venting systems for mitigation of radon and volatile organic compound vapor intrusion to protect the health of building occupants from inhalation exposures. The results indicate that the system performance depends strongly on the relative permeability of the floor slab and the material below the floor slab, and that both parameters can be determined with reasonable confidence using tests and analysis that are rapid and affordable. Where coarse granular fill is present below a high quality floor slab (typical in DoD building stock), the radius of influence may extend to considerable distances, which reduces the number of suction points required and the associated capital cost. Where a system already exists, mass emission monitoring may help reduce the operation, maintenance and monitoring costs.

**15. SUBJECT TERMS**
Vapor Intrusion Mitigation Optimization

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# EXECUTIVE SUMMARY

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| $\mu g/m^3$ | microgram(s) per cubic meter |
| | |
| AER | air exchange rate |
| AF | attenuation factor |
| ASD | active soil depressurization |
| | |
| DoD | U.S. Department of Defense |
| | |
| ft | foot/feet |
| $ft^2$ | square foot/feet |
| | |
| Pa | pascal(s) |
| | |
| scfm | standard cubic feet per minute |
| SSD | subslab depressurization |
| SSV | subslab ventilation |
| | |
| VI | vapor intrusion |
| VOC | volatile organic compound |

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# 1.0 INTRODUCTION

Subsurface vapor intrusion (VI) to indoor air of volatile organic compounds (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. SSD systems enhance SSV, and SSV systems cause SSD, so the terms are interchangeable to some degree. 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, EPA/625/5-88/024 (U.S. EPA 1988) recommended a minimum applied vacuum of 4 pascals (Pa) and ASTM E2121 (ASTM 2013) recommended a minimum applied vacuum of 6–9 Pa. Revisions to guidance documents are in progress at the time of this report (American National Standards Institute [ANSI]/American Association of Radon Scientists and Technologists [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, which was the motivation for this research.

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# 2.0 OBJECTIVES

The goal of this research was to demonstrate and validate a more rigorous and cost-effective process for design and optimization of systems for mitigating VI for VOCs and radon to reduce the capital and long-term operating costs. 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. This demonstration shows how a test procedure analogous to a groundwater pumping test can be performed very quickly and efficiently for subslab gas flow characterization and can be used with tracer testing, mass flux monitoring, and mathematical modeling to create several lines of evidence for performance assessment and monitoring to improve mitigation system design and operations.

Specific objectives included the following:

1. **Reduce Lifecycle Costs** associated with system design and installation, electricity to run fans, and energy loss due to conditioned (heated, cooled, humidified, or dehumidified) indoor air being drawn into the subsurface and vented to outdoor air and quantify these costs and recognized savings for comparison to the costs of performing the optimization.
2. **Maintain protection of indoor air quality** by maintaining indoor air concentrations below risk-based screening levels.
3. **Maintain a protective mass removal rate**, similar to or higher than the emissions of VOCs and radon through the building during building depressurization testing and/or comparable to the mass removal rate of an existing mitigation system where the optimization is performed after the initial system commissioning.
4. **Demonstrate and validate the technology** with sufficient data to allow a detailed review by third parties; include different buildings with a range of size and construction typical of U.S. Department of Defense (DoD) building stock, including residential buildings; engage a team of world-leading experts; and employ multiple lines of evidence, analytical modeling, and long-term monitoring,
5. **Transfer the technology** to DoD consultants and contractors so that it can be easily adopted and implemented at as many buildings as needed.
6. **Achieve regulatory approval.**

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# 3.0 TECHNOLOGY DESCRIPTION

The scope included field testing at four buildings ranging from 1,200 to 64,000 square feet (ft$^2$) in footprint size. Testing methods included monitoring of:

- ambient cross-slab differential pressure (ΔP) to establish building-specific target subslab vacuum levels (Figure 1);
- subslab vacuum versus time in response to fan cycles (on/off) (Figure 2) and subslab vacuum versus radial distance (Figure 3) for matching to Equations 1 and 4 to characterize the transmissivity (T) and leakance (B);
- subslab tracer testing (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;
- flow rate and VOC/radon concentrations in the vent pipes under various operating conditions to assess the mass removal rate as a function of gas extraction rate for comparison to threshold values of mass loadings via building pressure cycling and the system performance during challenges imposed by a stress test (Table 1); and
- mathematical modeling using the Hantush-Jacob (1955) Leaky Aquifer Model, after adjusting to account for different density between gas and water.

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 versus above the floor (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:

$$AF = \frac{T\,\Delta P}{B^2 h\, AER} \qquad \text{(Eq. 1)}$$

where T, ΔP, and B are defined above, h is the building height, and AER is the air exchange rate.

**Figure 1. Example of Ambient Cross-slab Differential Pressure Monitoring**

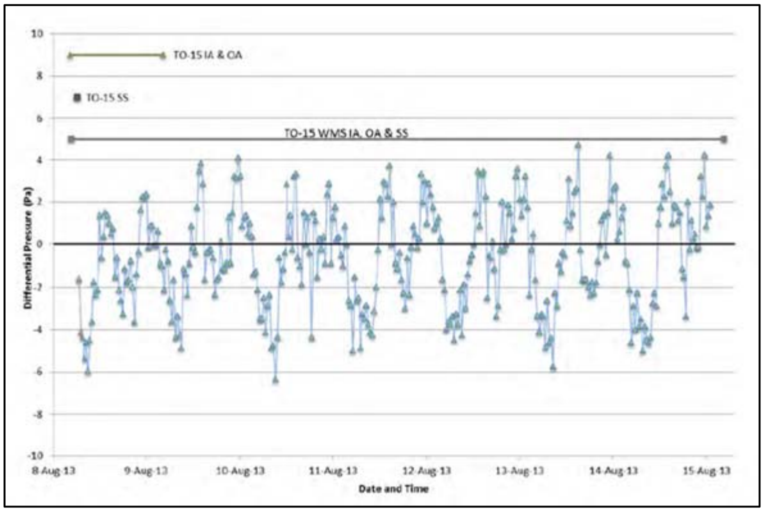


**Figure 2. Example of Subslab Vacuum versus Time: Raw Data (left), and Fit to the Hantush-Jacob Model (right)**

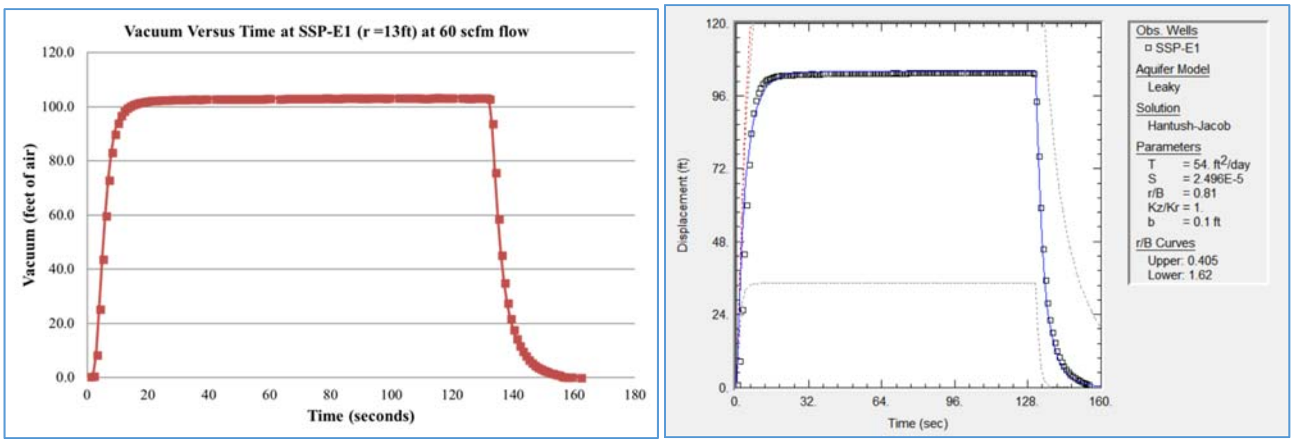


**Figure 3. Comparison of Vacuum versus Distance Measurements to Profiles Calculated Using the Hantush-Jacob Model**

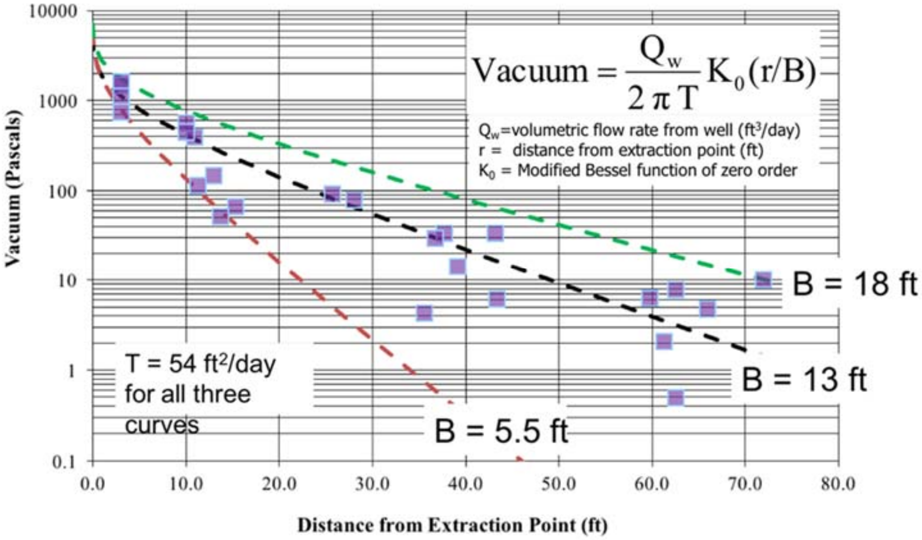


**Figure 4. Measured (left) and Modelled (right) Travel Time versus Distance from Suction Point**

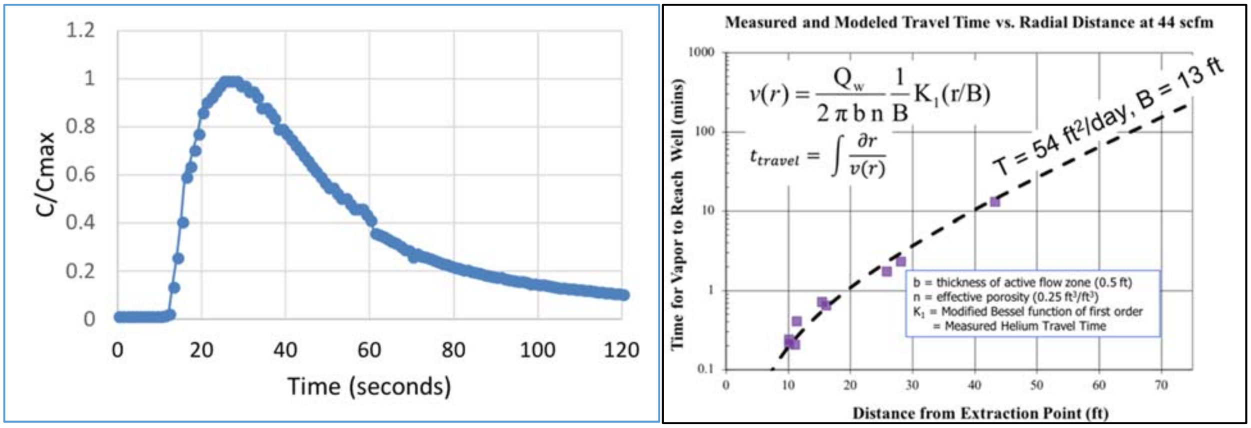
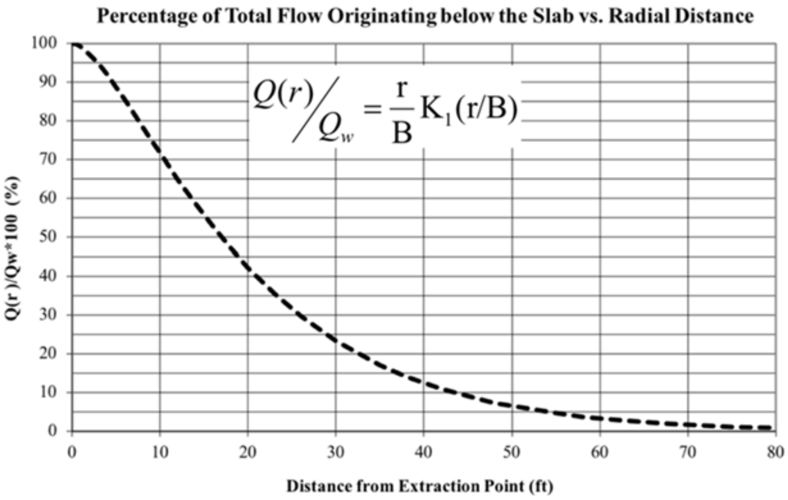


**Table 1. Mass Loadings for a Range of Operating Conditions**

| | | | PCE | | TCE | |
|---|---|---|---|---|---|---|
| SSV Flow Rate (CFM) | Blower Door Flow (CFM) | Duration (hr) | SSV Mass Loading (g/day) | Building Mass Loading (g/day) | SSV Mass Loading (g/day) | Building Mass Loading (g/day) |
| 50 | | 1 | 45 | | 1.0 | |
| | | 5 | 50 | | 0.79 | |
| 25 | | 1 | 24 | | 0.38 | |
| | | 16 | 22 | | 0.30 | |
| 25 | 5100 | 1 | 27 | 2.0 | 0.30 | 0.15 |
| 60 | 5100 | 1 | 67 | 1.9 | 0.74 | 0.18 |
| | | 17 | 50 | 1.3 | 0.52 | 0.10 |
| 65 | 5100 | 3 | 55 | 4.2 | 0.55 | 0.14 |
| 65 | 3800 | 1.5 | 52 | 5.7 | 0.55 | 0.13 |
| 60 | 3800 | 4.5 | 37 | 3.6 | 0.42 | 0.085 |
| 60 | | 22 days | 10 | | 0.26 | |

**Figure 5. Proportion of Flow Originating Below the Floor versus Radial Distance**



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# 4.0 PERFORMANCE ASSESSMENT

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 optimal spacing between suction points can be very large, which reduces the capital cost of installation for a large building compared to designs with closer spacing between suction points. Appendix B of this report provides a worked example of this scenario and shows that conventional design methods tend to underestimate the radius of influence (ROI) in this scenario. The DoD has a Unified Facilities Criteria Program (http://www.wbdg.org/ffc/dod) to ensure good and consistent construction practice and specifies 4–6 inches of reinforced concrete and 6–8 inches of ¾-inch granular fill that is gap graded to increase drainage rates (https://www.wbdg.org/guides-specifications/building-envelope-design-guide/below-grade-systems/floor-slabs). As a result, most new DoD buildings will fall into this category.

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 VOC transport into the building, so the conventional minimum subslab vacuum design criteria of 6–9 Pa (ASTM E2121) may not be necessary to prevent unacceptable exposures due to VI. 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. The subslab tracer testing, mass flux monitoring, and mathematical modeling developed during this research provide additional lines of evidence to support a protective design with smaller induced vacuums, a larger spacing between suction points, and/or lower fan power, which reduces capital and operating costs. The detailed example in Appendix B illustrates how conventional designs using a minimum specified static vacuum of 6–9 Pa result in an ROI estimate of 36 feet (ft), whereas the methods developed in this research demonstrate the ROI is up to about 90 ft. For a building with these characteristics and a floor area of 100,000 $ft^2$, a conventionally designed system would require 25 suction points drawing 2,500 standard cubic feet per minute (scfm) of soil gas whereas an optimized system would require only 4 suction points drawing 400 scfm. Use of the optimized system would be much less costly to install, operate, and maintain yet still meet all of the performance objectives. The permeability of the material below the floor and the leakance of the floor vary from building to building, so results will vary, but the test procedure includes building-specific measurement of these critical parameters as part of the optimized system design.

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.

Where the material below the floor has a low permeability and the subslab vapor concentrations are very high (i.e., >~1E6 micrograms per cubic meter [µg/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. Supplemental measures such as increased building ventilation, floor coating, or carbon filtration may be needed as interim measures until there is a reduction in subslab vapor concentrations.

For new construction, the use of "radon ready" construction with subslab collection pipes or aerated floors enables subslab ventilation with minimal effort and may be feasible with passive ventilation (driven by thermal gradients, wind-driven turbines, or solar-powered fans). Vapor barriers alone may be adequate in some cases, but they may also allow vapor concentrations to gradually increase to levels similar to those of the underlying source, and lead to diffusive transport across the barrier that could pose a threat to indoor air quality. Barriers will also inhibit the downward flux of oxygen, which is beneficial for natural degradation of petroleum hydrocarbon vapors and methane.

## 5.0 COST ASSESSMENT

The field methods developed to support mitigation optimization are relatively fast and simple with readily-available equipment and can be mastered by practitioners skilled in the art and sciences of hydrogeology, vapor sampling, and soil vapor extraction. The mathematical models are commercially available or readily programmed into a spreadsheet. As a result, the costs associated with implementing the lines of evidence developed in this research is modest compared to the potential savings in capital and operations, maintenance, and monitoring, so a net savings is to be expected, particularly for larger buildings. The testing program demonstrated that conventional methods for determining an ROI may result in a much greater number of suction points being installed than are really needed, which is costly and disruptive. The testing also shows that total system flow rates may commonly also be overdesigned, which wastes electricity to run the fans and incurs excess energy costs when conditioned indoor air is drawn through the floor and wasted by discharge to outdoor air.

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## 6.0 IMPLEMENTATION ISSUES

Implementation issues will be minimal for most DoD buildings. For rare cases where the floor slab rests on very low permeability native soil, subslab venting systems may not achieve sufficient flow or mass removal to be protective of indoor air and alternatives such as aerated floor, increased building ventilation, and/or barriers may be needed. For new construction, it may be preferable to use aerated floors or other options, in which case the analysis developed here would not be needed. Adoption of this technology into written standards may take some time.

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# 7.0 REFERENCES

ASTM E 2121-13 (initially issued in 2001, latest revision 2013). Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

U.S. EPA, 1988. “Application of Radon Reduction Methods," EPA/625/5-88/024, August 1988

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# APPENDIX B. WORKED EXAMPLE OF HIGH AND LOW T AND B VALUES

Consider two cases: one with coarse sand below a concrete slab (T = 10 ft$^2$/day, hereafter referred to as LowT) and one with gravel (T = 1,000 ft$^2$/day, hereafter HighT). For both cases, assume the leakance factor (B) is the same at 15 ft (the influence of high and low leakance is described further below). In both cases, assume a fan with a power of about 100 watts is used to draw gas from the subsurface. The flow from the gravel would be higher than the flow from the sand, for the sake of this example, assume 100 standard cubic feet per minute (scfm) from the gravel and 10 scfm from the sand. These values are all consistent with observations made by Geosyntec at over 120 pneumatic tests of subslab gas extraction (McAlary et al., 2018). The profile of vacuum vs radial distance calculated using Equation 4 would be as shown in Figure B-1. If the radius of influence (ROI) was based on the minimum vacuum recommended by ASTM E2121 (6 Pa), the ROI would be about 67 ft for the LowT case and about 36 ft for the HighT case. This corresponds to an area of influence (3.14 x ROI$^2$) of 4,100 ft$^2$ for the HighT case and 14,000 ft$^2$ for the LowT case. If the building of interest had a footprint of 100,000 ft$^2$, the LowT case would likely employ about 7 suction point, whereas the HighT case would likely employ about 25 suction points. The total flow from the LowT system would be about 70 scfm, and the total flow from the HighT system would be about 2,500 scfm to achieve a vacuum below the floor greater than or equal to 6 pascals everywhere.

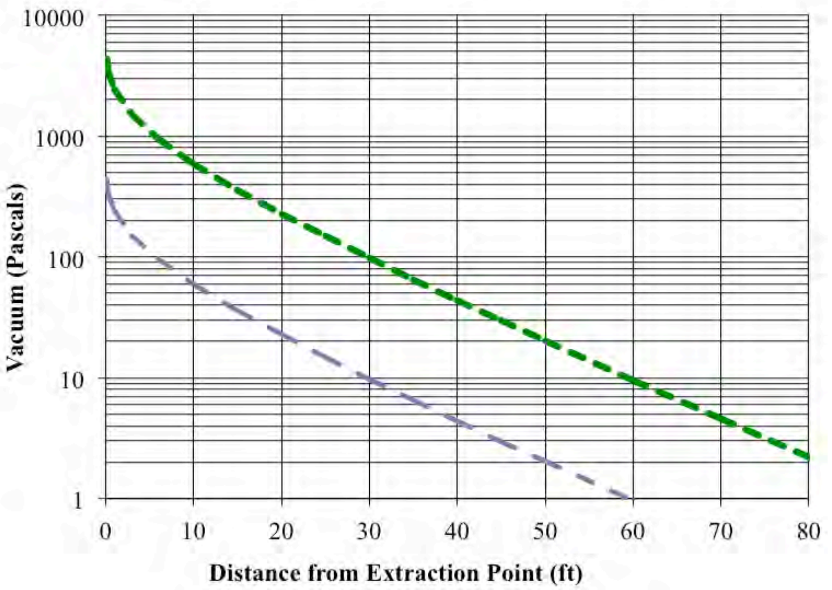

**Figure B- 1: Vacuum vs distance calculated using Equation 4 and a B value of 15 ft for the LowT (green) and HighT (purple) cases described in the text above**

The subslab velocities for the same two cases described above can be calculated with Equation 5, and are shown in Figure B-2. The HighT case has velocities about an order of magnitude higher than the LowT case because of the difference in the gas extraction rates (100 scfm vs 10 scfm).

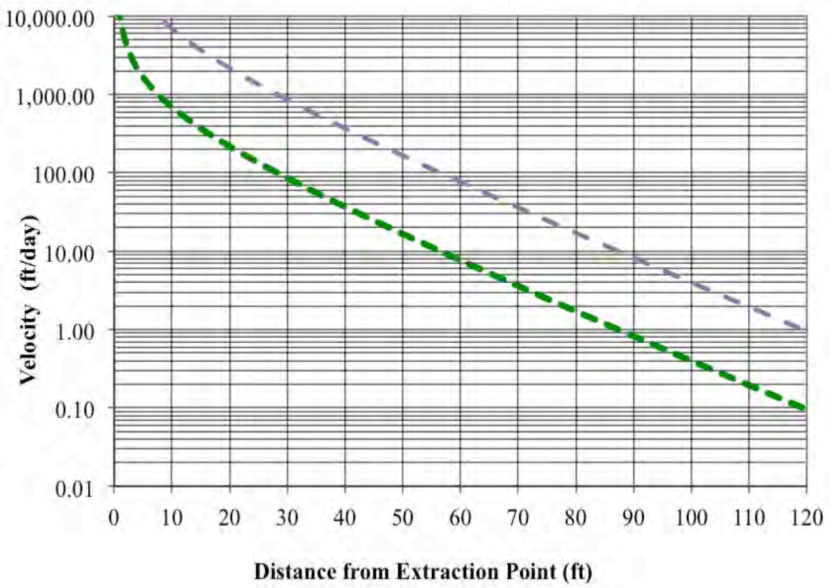

**Figure B- 2: Velocity vs distance calculated using Equation 3 and a B value of 15 ft for the LowT (green) and HighT (purple) cases described in the text above**

Figure B-2 shows that at the radii corresponding to 6 pascals vacuum, the induced flow velocities are about 6 ft/day for the LowK case and about 600 ft/day for the HighK case. If a goal of 3 ft/day induced velocity was used for a performance criteria, the radius of influence would be about 70 ft for the LowK case (very similar to the radius where vacuum = 6 Pa). But for the high T case, the ROI would be over 100 ft and at that radius, the applied vacuum would be much less than 0.1 pascal (inferred from extrapolation of the trend on Figure B-1), which is below the lower limit of sensitivity of most micromanometers and usually not distinguishable from fluctuations in the baseline pressure differential (and is more than 100 times lower than the target vacuum specified in ASTM E2121). This demonstrates the reason that vacuum alone is not an ideal performance metric and the permeability of the material below the floor is very important.

The travel times from different radial distances can be calculated using Equation 6, as shown in Figure B-3.

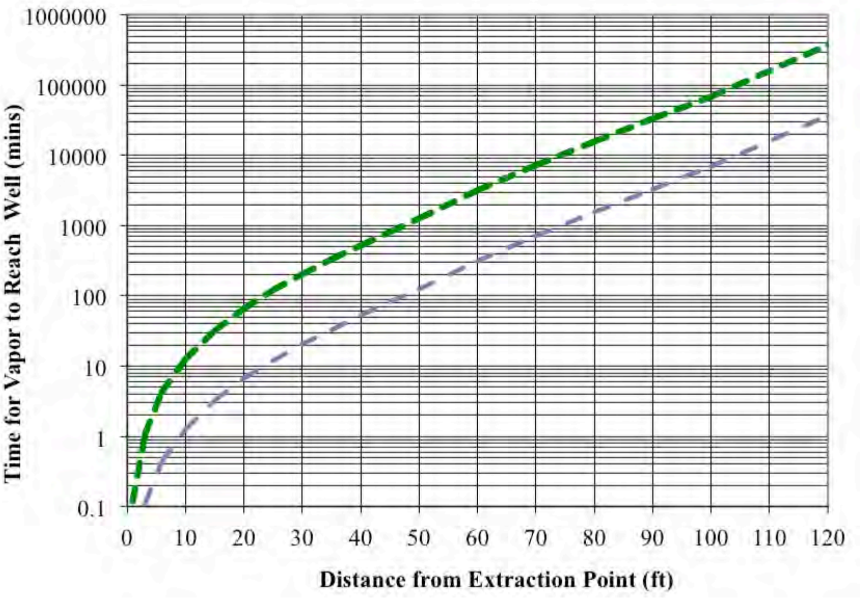

**Figure B- 3: Travel time vs distance calculated using Equation 4 and a B value of 15 ft for the LowT (green) and HighT (purple) cases described in the text above**

For the LowT case, where ROI based on 6 pascals of vacuum was 67 ft, the corresponding travel time is about 3.5 days. For the HighT case, where the ROI based on 6 Pa of vacuum was 37 ft, the corresponding travel times is about 30 minutes (170 times faster). This provides an insight into the rate of subslab ventilation (not just depressurization). For the hypothetical building of 100,000 $ft^2$ described above, the HighK system of 25 suction points and a total flow rate of 2,500 scfm would ventilate the region below the floor with an air exchange rate 170 times higher than the LowT system with 7 suction points and a total flow of 70 scfm. Note that this is not intuitive because the ratio of the system flow rates (2500/70) is 35x, not 170x. The reason for the difference is the system with larger suction-point spacing draws more air from leakage across the floor slab, and less from the subsurface, as described further below.

If the venting system was designed to remove gas from the granular fill at least once every 0.1 day, Figure B-3 shows the LowT case would be effective to a radius of about 25 ft and the HighT case would be effective to a radius of about 50 ft. For the hypothetical 100,000 $ft^2$ building, this would result in a system in the HighT case of 13 suction points and a total flow of 1300 scfm, and a system for the LowT case with 51 suction points and a total flow of 510 scfm. Not all cases are as bad as the 95th percentile of the AF distribution, so these designs may be excessive in many cases, in which case, the building-specific attenuation factor may be useful to consider. Monitoring subslab concentrations and mass removal rates could be used to optimize the total extraction flow rate over time to maintain subslab vapor and radon concentrations at a level that poses no unacceptable risk.

The proportion of flow originating below the floor as a function of the radial distance from the point of suction can be calculated using Equation 7 and is shown on Figure B-4 for the HighT and LowT cases. Note that Equation 7 depends only on the leakage factor (B), and not on T, so the two cases result in the same relation. This chart provides information regarding the distance to which the venting system draws a significant flow from the subsurface. For the HighT case, the radius corresponding to 6 pascals vacuum is about 36 feet, and at that radius about 20% of the flow from that distance originates in the subsurface vs 80% from leakage across the floor slab. The flow in the high T case is 100 scfm, and 20% of 100 scfm is 20 scfm. For the LowT case, the radius corresponding to 6 pascals vacuum is about 67 feet, where about 3% of the flow originates from the subsurface. The flow in the LowT case is 10 scfm and 3% of 10 scfm is 0.3 scfm (67x lower than the HighT case). For reference, EQM (2004) recommended a value of 5 L/min (0.18 scfm) as a conservative default Qsoil value for use in the U.S EPA spreadsheet implementation of the Johnson and Ettinger (1991) Model (this is for a residence with an assumed 10m x 10 m footprint).

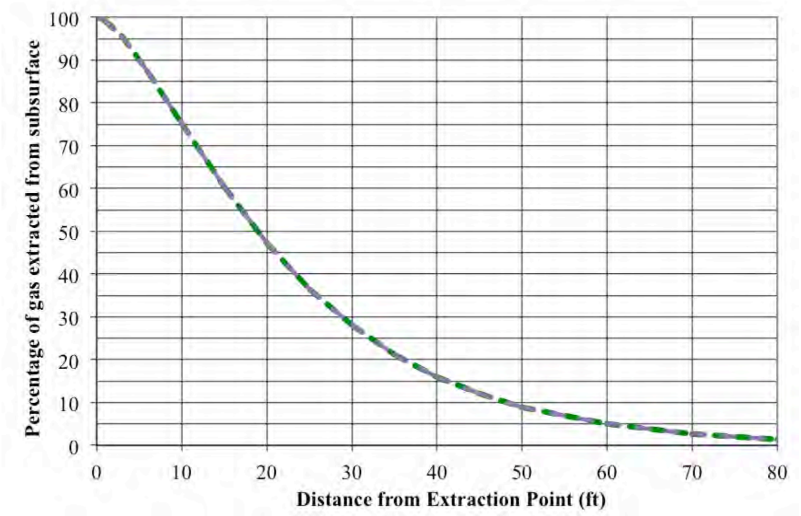

**Figure B- 4: Proportion of flow originating below the floor vs distance using Equation 5 and a B value of 15 ft for the LowT (green) and HighT (purple) cases described in the text above**

Figure B-5 shows the downward vertical flow across the floor for the two cases, expressed in units of L/min per 1000 ft$^2$ of floorspace. For the 10 scfm flow rate in the LowT case, the threshold of 5 L/min per 1000 ft$^2$ corresponds to a radius of about 53 ft. For the 100 scfm flow rate of the HighT case, the radius corresponding to 5 L/min per 1000 ft$^2$ of floor space would extend to approximately 90 ft.

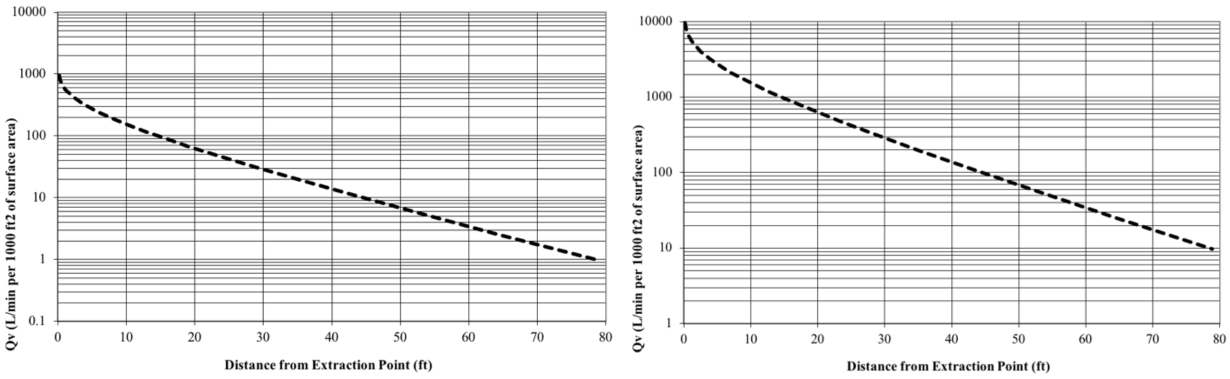

**Figure B- 5: Vertical flow per 1000 ft2 of floor area for 10 scfm (left) and 100 scfm (right)**

Equation 7 can also be used to estimate the energy cost of loss of conditioned air. For the HighT case, at the ROI corresponding to a vacuum of 6 Pa (36 ft), 80% of the extracted gas originates from leakage of indoor air (or 80 scfm). For the LowT case, at the ROI of 67 ft corresponding to a vacuum of 6 Pa (67 ft), the loss of conditioned air would only be 9.7 scfm. This yields almost an order of magnitude difference in the energy costs between the two cases.

The HighT and LowT cases used the same B value for simplicity. The sensitivity of the B value for these relations can also be explored. Consider a scenario with an intermediate transmissivity of 100 $ft^2$/day and flow rate of 50 scfm from a suction point. A HighB case might have a B value of 25 ft (this corresponds to a relatively competent floor slab) and a LowB case might have a B value of 7 ft (corresponding to a relatively leaky slab). Figure B-6 shows the four plots from Equations 4, 5, 6, and 7. The vacuum vs distance chart shows that the profile of vacuum extends much farther when the floor is less leaky. Many mitigation practitioners already measure applied vacuum at more than one radial distance as part of performance testing, and these data can be used to calibrate the vacuum vs distance profile to the B value using the model, which can be done in real time using a spreadsheet very quickly and at low cost. Note that the two curves converge at radius = 0, this is because the vacuum at the point of suction depends primarily on T and not B. Therefore, if vacuum is also measured at a small radial distance, the T value can also be calibrated by fitting the vacuum versus distance data to Equation 4.

Once the T and B values are calibrated to the vacuum vs time and vacuum vs distance data, the plot of travel time versus distance is easily generated using Equations 5 and 6. The travel time versus distance plot can be used to select a radial distance for an inter-well tracer test (for this plot, a travel time of a few minutes would correspond to a radial distance of about 10 feet for either leakage value). The tracer test can be used to verify the thickness of the zone through which the majority of gas flow occurs (b), which is a parameter in Equation 5 (but not in Equation 1 or 4, so the b value does not influence the profiles of vacuum vs time or vacuum vs distance). Once the T, B and b values have been calibrated, the model can be used to calculate the relative proportion of flow from below the floor vs distance using Equation 7.

For the leaky case (B = 7 ft, shown as the blue dashed line), the ROI corresponding to 6 pascals of vacuum is about 26 ft, but if the performance criteria included <0.1-day travel time, >3 ft/day velocity or >5L/min flow from the subsurface per 1000 $ft^2$ of area, the radius of influence would be 30 feet or more. For the competent slab (B = 25 ft, shown as the red dashed line), the radius of influence would be 60 feet for a travel time of 0.1 day and greater for all the other lines of evidence. The radius of influence has a direct impact on the number of suction points required to provide protection for a given footprint of building. The area of influence is simply π multiplied by the square of the radius of influence. The target treatment area divided by the area of influence provides a minimum number of suction points. Additional suction points may be appropriate if there are subsurface barriers such as bearing wall footers or preferential pathways such as subfloor utilities.

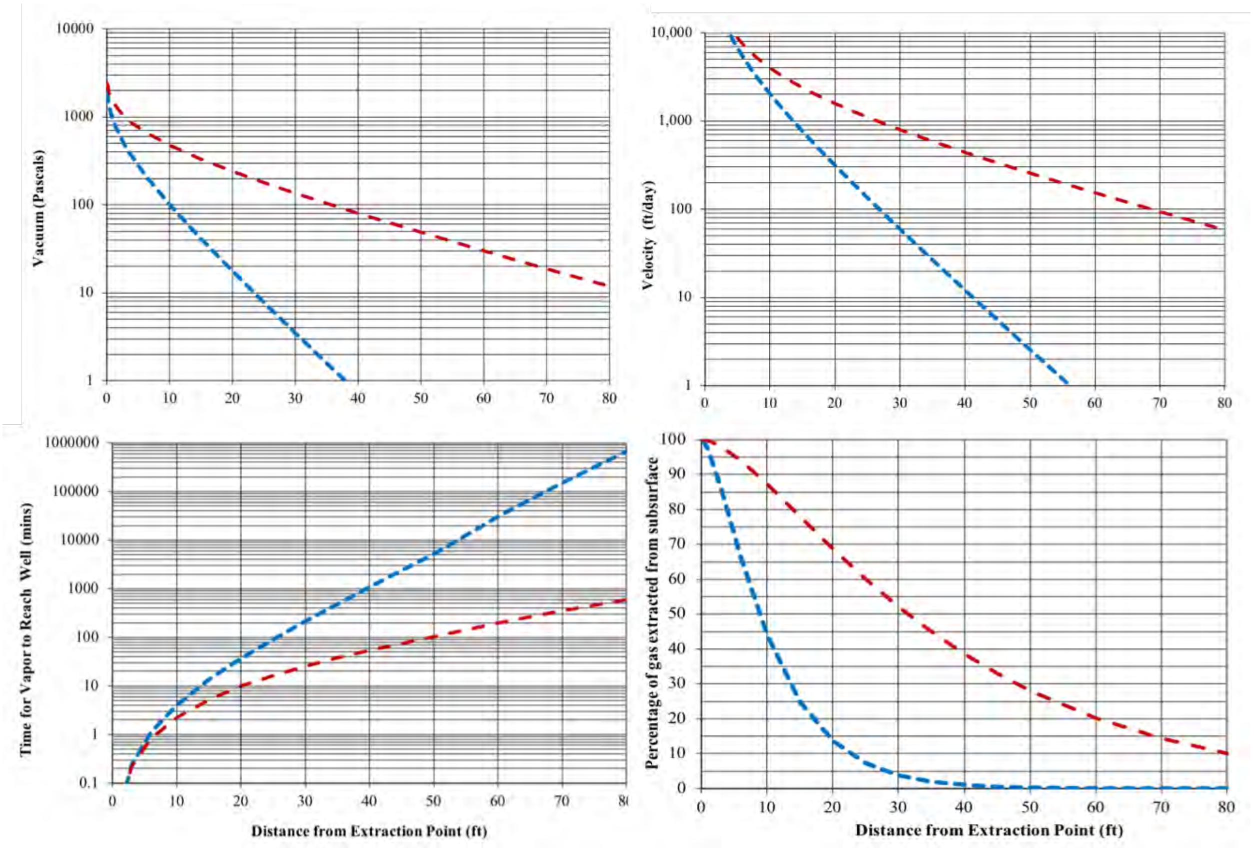

**Figure B- 6: Plots of vacuum, velocity, travel time and proportion of flow from beneath the floor slab vs distance for the HighB (red) and LowB (blue) cases described in the text above**

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