RESILIENT INFRASTRUCTURE
June 1–4, 2016
RESILIENT INFRASTRUCTURE LONDON 2016

USE OF NEW MODELS TO SUPPORT VAPOUR INTRUSION MITIGATION DESIGN

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ABSTRACT

Soil vapour intrusion of subsurface volatile organic compounds (VOCs) into indoor air of buildings is a significant potential concern at existing sites where chemical releases occur, or at new buildings at Brownfield sites with residual chemical impacts. While soil vapour intrusion mitigation systems are increasingly being implemented, there are limited published data on mitigation performance for VOCs particularly for industrial or commercial buildings or high density residential buildings with below ground parking garages. Data gaps include the effectiveness of passive and active venting systems and reduction in vapour intrusion that can be achieved relative to unmitigated buildings. Because of lack of knowledge and standardization, design practices and post-mitigation monitoring requirements vary widely and are, in some cases, over-conservative. To address these gaps, a comprehensive empirical review of data on the performance of active and passive venting systems and a study using the Modified Johnson and Ettinger Model was completed. The empirical data indicate performance of passive venting systems are variable in terms of venting air flow rates and pressures. The results of modelling for passive venting indicate a wide range of predicted reduction factors, defined as the vapour attenuation factor for a baseline unmitigated building divided by the attenuation factor for the mitigated case. Because of the potential for depressurized buildings and/or reverse vent stack effect, for passive venting systems a continuous leak free barrier that reduces the potential for soil gas diffusion and advection is essential. The performance of active venting systems can be more readily controlled and quantified based on design principles as supported by the results of modelling, which indicated higher reduction factors than for passive venting systems. For both passive and active venting systems, improved efficiency in venting can be achieved through aerated subfloors. A monitoring framework that is robust but efficient and sustainable is presented that incorporates the concept of a concentration exceedance factor and the type of mitigation system.

Keywords: vapour intrusion, mitigation, passive venting, active venting, design, optimization, sustainability

1. INTRODUCTION

Soil vapour intrusion of subsurface volatile organic compounds (VOCs) into indoor air of buildings is a significant potential concern at existing sites where chemical releases occur, or at new buildings at Brownfield sites with residual chemical impacts. Generic models utilizing subsurface concentration data or indoor air quality measurements often predict unacceptable potential health risk and consequently risk management measures (RMM) such as vapour intrusion mitigation systems are increasingly being required. While there is several decades of experience for radon mitigation, there are limited published data on soil vapour mitigation performance for VOCs particularly for industrial or commercial buildings or high density residential buildings with below ground parking (storage) garages. Data gaps include the effectiveness of passive and active venting systems and reduction in vapour intrusion that can be achieved relative to unmitigated buildings. Because of lack of knowledge and standardization, design practices and post-mitigation monitoring requirements vary widely, and in some cases, overly-conservative approaches are being followed.

This study addresses these gaps through a comprehensive review of empirical data on soil vapour intrusion mitigation system performance and a modelling study that evaluates key factors for mitigation. The objectives of this study are to develop a better understanding of the performance and sustainability of different vapour intrusion mitigation methods and an improved framework for mitigation and monitoring that is efficient and that is tied to an concentration exceedance ratio concept, which is a measured or predicted indoor air concentration divided by an acceptable indoor air concentration (e.g., regulatory standard). The intended outcome is a more stream-lined and sustainable approach for vapour intrusion mitigation.

2. SUMMARY OF SOIL VAPOUR INTRUSION MITIGATION METHODS

Soil vapour mitigation options for existing buildings include: 1) subslab depressurization (SSD) or subslab ventilation (SSV); 2) building pressurization and increased ventilation; 3) soil vapour extraction; and 4) air purification. SSD and SSV require that larger openings in the building envelope such as open perimeter cracks and drains are sealed. SSD or SSV are similar technologies with slightly different operational objectives. The intent of SSD is to create a slight negative pressure below essentially the entire foundation slab to prevent soil gas advection into a depressurized building, while through venting, SSV removes or dilutes vapours that could potentially migrate to the building. A SSV will also create negative pressures below the foundation slab to varying degrees.

Building pressurization and increased ventilation requires modifications to the building heating, ventilation and air conditioning (HVAC) system. The potential drawbacks of this method include cost of heating or cooling additional air and challenges in consistently pressurizing the building air space. There is also the potential for increased moisture in the building and mold. When buildings have exhaust-only ventilation systems, balancing of air intake and exhaust through installation of a heat recovery ventilator (HRV) can reduce vapour intrusion, as reported in the radon literature. Soil vapour extraction can be an effective approach for deeper contamination zones and coarse-grained soils. Air-purifying units may be a short-term option for addressing vapour intrusion but there are limited published data on their effectiveness.

For future buildings, in addition to installing a passive or active venting system, a geomembrane barrier may be installed below the building foundation, which is warranted for passive systems, but may not be required for active systems depending on the reduction in vapour intrusion required and venting design. There is opportunity for engineering and optimization of the barrier layer, venting layer and system energy (i.e., wind, electrical fan). For this study, passive venting is defined to include wind turbines, while active venting is mechanically powered. Guidance on soil vapour intrusion mitigation is provided in ITRC (2015) and US EPA (2008).

3. REVIEW OF EMPIRICAL DATA ON SOIL VAPOUR INTRUSION MITIGATION

Forty-one published studies with empirical vapour mitigation performance data for VOCs, radon and methane were reviewed. Twenty-two studies were for residential houses and fifteen studies were for institutional, commercial and/or industrial buildings. For the majority of the studies, the mitigation technology was active SSD, with 64% of residential buildings and 73% of institutional, commercial or industrial buildings mitigated using this method. Other mitigation technologies employed were passive venting, building pressurization (infrequent) and soil vapour extraction (infrequent).

Published case studies of mitigation performance for new buildings at Brownfields were limited to institutional, commercial or industrial buildings, with no data for residential buildings. The authors are, however, aware of high density residential condominiums with underground parking garages where risk assessments have incorporated the reduction in vapour intrusion due to increased ventilation and size of parking garages. Existing or proposed regulatory frameworks in Ontario and British Columbia include less conservative vapour attenuation factors (indoor air concentration divided by the soil vapour concentration) for parking garages depending on the scenario considered thereby avoiding needless mitigation where appropriate.

3.1 Existing Buildings

The results of literature review of active and passive SSD performance for existing buildings are presented in **Tables 1** and **2**. All but one case study was for single family houses. The SSD performance was quantified as the reduction in post-mitigation indoor air concentrations relative to pre-mitigation concentrations (percentage and a reduction multiplier). The buildings in the case studies reviewed had venting layers comprised of sand and gravel. The results in **Tables 1** and **2** indicate active venting is significantly more effective than passive venting. The active venting case studies reviewed generally showed at least 80% (5X) reduction in post-mitigation concentrations, compared to 50% (2X) or less reduction for passive venting systems or one study where just floor drains were sealed.

Table 1: Active SSD Performance for Existing Buildings – Chemical Monitoring Results

Study	Building	Chemical	Performance[1]
Lund et al. (2015) – New Mexico, USA	Commercial N = 6	Perchloroethylene (PCE)	91% - >99% 11X - >100X
Eernisse et al. (2009) – Utah, USA	Houses N = 50	Trichloroethylene (TCE)	84% 6.2X
Folkes & Kurtz (2002) – Colorado, USA	Houses N = N/A	1,1-DCE	2-3 orders of magnitude[2] 100X - 1000X
Hannu (2010) – Finland	Houses N = N/A	Radon	70% - 90% 3.3X – 10X
Paridaens et al. (2005) – Belgium	Houses N = 1	Radon	90% 10X
Jiránek (2014) – Czech Republic	Houses N = 62	Radon	70% - 98% 3.3X – 50X
Golder (unpublished) – Confidential Site, Canada	Houses N = 26	TCE	80 - 99% (Avg = 94%) 5X – 100X (Avg = 26X)

Notes: [1] Reduction in post-mitigation indoor air concentrations compared to pre-mitigation concentrations; [2] Action levels were achieved in 75% of houses for the initial system, while for 25% additional measures were required to achieve action levels. N = number of buildings. N/A = not available.

Table 2: Passive Venting Performance for Existing Buildings – Chemical Monitoring Results

Study	Building	Chemical	Performance[1]
Holford and Freeman (1996) – Washington (State), USA	House N = 1	Radon	30% 1.4X
Weiffenbach and Marshall (2003) – Wisconsin, USA	Houses N = 8	Radon	25% - 87% 1.3X - 8X
Hannu (2010) – Finland	Houses N = N/A	Radon	50% 2X
Warkentin and Johnson (2015) – Manitoba, Canada	Houses N = 50	Radon	47% (just drain seal installed) 2X

Notes: [1] Reduction in post-mitigation indoor air concentrations compared to pre-mitigation concentrations. N = number of buildings. N/A = not available.

There were three additional case studies with data on pressure and flow for passive venting systems of existing buildings, which are summarized below:

- Abdelouhab et al. (2010) reported data from a test house in France where the pressure difference between the subslab vapour vents and house was measured. During the winter, the differential pressure was less than -1 Pascal (Pa) indicating that the stack effect was causing venting of soil gases. During the summer, the pressures were neutral or positive indicating poor venting performance. With a wind-turbine connected to the vent, the performance in terms of vent air flow improved by approximately two-times.
- Weiffenback and Marshall (2003): Eight houses in Wisconsin were monitored for subslab pressures. Data indicate subslab vents were under negative pressure, but sumps located at varying distances from the vents were under positive pressure indicating poor pressure extension.
- Lutes et al. (2015): At two duplexes, the differential pressure between the subslab venting layer and house was monitored. The differential pressure was greater than zero much of the time and as high as 3-5 Pa indicating poor performance.

The lessons learned from these studies include the variable effectiveness of passive venting for existing buildings, with poorer performance potentially in summer because of reverse stack effect in vents where warm air moves down the stack. Limited data indicate wind turbines can improve venting performance.

3.2 New Buildings

For new buildings constructed at Brownfields, it is not possible to quantify the performance of a mitigation system with respect to pre- and post-mitigation indoor air concentration data. However, it is possible to infer performance from monitoring data of pressure and flow (**Tables 3** and **4**).

Table 3: Active Venting Performance for New Buildings – Air Flow Data

Study	Building Type	Venting Material	Mitigation System	Building Footprint Area (m^2)	Venting Layer Void Volume (m^3)	Measured Air Flow Rate (m^3/hr)	Venting Layer Air Change Rate (hr^{-1})
1. Folkes. (2008)	Rec centre w\ basement	Gravel	4 blowers	1858	99.1	10.8	6.6
2. Al-Ahmady & Hintenlang ('96), Florida, USA	Commercial building	Gravel	Single fan (0.1 HP)	773	41.2	3.96	5.8
3. Jourabchi et al. (2015), Ontario, Canada	Commercial building	Gravel	1 blower (1.5 HP)	899	63	5.66	5.4
4. Hers & Hood (2012), Ontario	Commercial building	Aerated Subfloor	2 fans (0.2HP ea)	8880	1332	57.6	2.6
5. Hers & Hood (2012), Ontario	Commercial building	Aerated Subfloor	1 fan (0.2 HP)	1750	262	24	5.4
6. Hers & Hood (2012), Ontario	Commercial building	Aerated Subfloor	1 fan (0.2 HP)	2200	329	26	4.7
7. Folkes (2011)	Commercial building	Aerated Subfloor	1 fan (0.03 HP)	400	75	4.6	3.7

Notes: Gravel venting layer thicknesses are 0.15 m for Studies 1 & 2 and 0.2 m for Study 3. Aerated floor thicknesses are 0.2 m. Assumed gravel and aerated floor porosities are 0.35 & 0.75, respectively. Commercial buildings had slab-at-grade foundations.

Case studies of active venting systems indicate pressures generally met the ASTM 2121 criteria of 6-9 Pa negative pressure in the venting layer below more than 90% of the building (Al-Ahmady and Hintenlang 1996; Jourabchi et al. 2015; Hers and Hood 2012). A significant advantage of aerated subfloors compared to gravel venting beds is more consistent negative pressures (Hers and Hood 2012; Folkes 2011). The case studies reviewed indicate pressure criteria were also met for aerated subfloors using relatively small, low energy fans (**Table 3**). Higher air flows were obtained for aerated subfloors at lower energy cost than gravel venting layers because of lower frictional losses. The reported air flow rates for fans were divided by the estimated volume of the venting layer void space to obtain the venting layer air change rate. Similar venting layer air change rates were obtained for gravel and aerated subfloors because of the larger void space per unit area for aerated subfloors. A lesson learned from these studies is that improved venting performance can be achieved through aerated subfloors.

Case studies of passive venting systems reported soil gas air flows out of the vent stacks and inferred or measured negative pressures in vent stacks (**Table 4**). All three studies described mitigation systems comprised of a barrier, gravel venting layer and a series of vent pipe laterals. The study by Reinis et al. (2006), which was for two buildings at methane-impacted sites, indicated higher vent stack air flows of 4.9 to 32 cubic feet per minute (cfm) compared to those measured at 28 buildings with a range of soil gas impacts (methane, VOCs) where stack air flows were 0.6 to 13.1 cfm. The higher air flows for Reinis et al. (2006) compared to Reinis et al. (2012) were, in part, attributed to shorter air entry pipes and lower frictional losses. Negative vent pipe pressures were inferred during seasonal monitoring for all three studies, and for Reinis et al. (2006), while vent stack air flow was correlated to wind speed, positive air flow rates out of the stack were measured even during calm days (likely due to stack effect). Reinis et al. (2012) include data that indicate venting performance decreased as the outdoor temperature increased, likely because of reduced or absent stack effect. The lessons learned include that performance of passive venting systems are influenced by weather conditions and piping and venting systems should be optimized to reduce frictional losses. Negative pressures and positive outflows of soil gas from vent stacks are important for reducing the reliance of passive mitigation on the barrier system.

Table 4: Passive Venting Performance for Existing Buildings – Air Flow and Pressure Data

Study	**Building**	**Vent Stack Air Flow Rate (cfm)**	**Comments**
Reinis et al. (2012) – Oakland, CA, USA	Commercial N = 28	0.6 - 13.1 (mean 5.9)	Negative ΔP inferred, venting performance decreased with increasing ambient temperature
Reinis et al. (2006) – Oakland, CA	Commercial N = 2	4.9 - 32 (mean 13)	Negative ΔP inferred, flow rate correlated to wind speed, but air flow measured even under calm conditions
Golder (unpublished) – Vancouver, BC	Commercial N = 2	1.2 cfm at wind speed = 1.4 m/s	Pressure = - 6.5 Pa (0.026 in w.c.) in vent stack, temperature in stack ~ 3ºC > ambient temperature suggesting potentially significant vent stack effect

Notes: w.c. = water column; ΔP = pressure difference between venting layer and ambient or building air

4. MODELLING STUDY OF PERFORMANCE OF SOIL VAPOUR MITIGATION SYSTEM

The performance of passive and active venting systems for new buildings was evaluated through a modelling study where predicted vapour attenuation factors for a baseline scenario without mitigation were compared to scenarios with mitigation. The model used for this study, the Modified Johnson and Ettinger (J&E) Model, is a semi-analytical spreadsheet model developed by Golder based on the Johnson and Ettinger (1991) model framework.

4.1 Model Description

The Golder Modified J&E model is a multi-compartment model that can simulate different scenarios for passive and active venting, including a venting layer comprised of an aerated subfloor or gravel layer. The model enables air concentrations to be predicted in a sub-building compartment, consisting of a parking garage, basement, or crawlspace, and a main building compartment (e.g., building enclosure above a parking garage). The model includes options for vapour barriers below the sub-building and between the two building compartments.

The Modified J&E model assumes that there is a laterally continuous, constant-in-time, non-depleting soil vapour or groundwater source located below the building. The model utilizes the SOLVER routine in EXCEL to calculate the upward diffusive mass flux in an unsaturated soil zone, mass flux removed through a venting layer (if present), mass flux through soil gas advection into a sub-building compartment (if operable), diffusive mass flux through a building foundation and instantaneous mixing of vapours in sub-building and building air spaces. The model has been successfully benchmarked to the US EPA Superfund Johnson and Ettinger spreadsheet for the case where there is no mass removed through a sub-building or venting compartment (i.e., model collapses to the Johnson and Ettinger (1991) solution). The Modified J&E model also includes diffusion through the concrete foundation as an option in addition to diffusion through dust-filled cracks in concrete.

4.2 Modelling Scenarios and Model Input Parameters

The Modified J&E Model was used to predict vapour attenuation factors for trichloroethene vapour intrusion for an industrial or commercial type building with slab-at-grade construction for a baseline scenario without vapour mitigation and mitigation scenarios where the soil gas advection rate (Q_{soil}), the venting layer ventilation rate (Q_{vent}) and foundation crack ratio were varied, as follows:

1) Case 1: Passive venting with barrier - Q_{soil} and Q_{vent} varied
2) Case 2: Active venting without barrier – Q_{vent} varied
3) Case 3: Active venting without barrier – Crack Ratio varied

For passive venting, Q_{soil} was varied because of the potential for buildings to be depressurized under certain weather conditions (e.g., due to reverse stack effect). The input parameters for the modelling are provided in **Table 5**.

Table 5: Input Parameters for Modified Johnson and Ettinger Model

Parameter	Unit	Value	Parameter	Unit	Value
Building width	(m)	20	Building height	(m)	3.0
Building length	(m)	15	Distance of building to vapour source	(m)	0.3
Foundation thickness	(-)	0.11	Air-filled porosity	(-)	0.39
Crack width	(mm)	1	Total porosity (gravel)	(-)	0.40
Foundation crack ratio[1]	(-)	2.3E-04	Soil gas advection rate[1] (Q_{soil})	L/min	9.8
Air change rate	(hr^{-1})	1	Venting Layer Ventilation Rate[1] (Q_{vent})	(hr^{-1})	0

Note: Above inputs are the Ontario MOECC Modified Generic Risk Assessment Model (MGRA) inputs for an industrial building and coarse-grained soil. [1]Parameter values vary and those for the Baseline No Venting Scenarios are shown.

4.3 Modelling Results

Baseline No Venting: For this scenario, a Q_{soil} of 9.8 L/min was assumed based on the Ontario Ministry of Environment and Climate Change (MOECC) default value for an industrial building scenario. The calculated attenuation factor was 6.1 x 10^{-4}.

Passive Venting with Barrier – Q_{soil} and Q_{vent} Varied: For this scenario, Q_{soil} was varied from 4.9 L/min to 0 L/min and Q_{vent} from 0 to 0.5 hr^{-1}. The values are considered to span the range of plausible inputs for poor to good venting performance. Poor venting performance is characterized by soil gas advection into a depressurized building equal to Q_{soil} of 4.9 L/min (arbitrarily assumed to be half of Q_{soil} for the unmitigated building). Good venting performance is characterized by no soil gas advection with some ventilation of the venting layer with Q_{vent} equal to 0.5 hr^{-1}. The barrier layer thickness (1.5 mm) and permeation rate (2 x 10^{-12} m/s) were estimated based on published values for Liquid Boot and Geo-Seal (Olsta, 2010 and manufacturer's data) and 80 mil HDPE (McWatters & Rowe, 2010). The defect ratio, assumed to be 7.5 x 10^{-8} (dimensionless value), was based on landfill studies (Needham et al. 2006, Schroeder et al. 1994; Giroud and Bonaporte 1989; Rowe et al. 2003). The defect ratio was only used to adjust diffusion through the building foundation and not Q_{soil}.

The modelling results are presented as vapour attenuation factors and reduction factors, defined as the baseline attenuation factor of 6.1 x 10^{-4} divided by the attenuation factor for mitigation scenario considered. The reduction factors range from two to 507 (**Figure 1**). The results indicate that the influence of a barrier is small when soil gas advection is assumed to occur because of openings in the liner and a depressurized building. This assumption is overly conservative but is included to illustrate the importance of a continuous, leak free liner for passive venting systems (and maintenance to prevent future leaks) where the barrier is relied upon to reduce soil gas diffusion and advection into a building. The scenarios with no soil gas advection are considered to be generally more representative. The model predictions were insensitive to properties of the barrier for input parameters considered.

Active Venting without Barrier – Q_{vent} Varied: For this scenario, Q_{soil} was 0 L/min, and Q_{vent} was varied from 0.1 L/min to 10 L/min. The corresponding reduction factors range from 507 to 5159 (**Figure 2**). Given that the empirical data indicated air flow rates in gravel beds and aerated subfloors were greater than about 2 L/min (**Table 3**), representative reduction factors are greater than 1000. The high end of the range of reduction factors may be unrepresentative because the model assumes uniform venting. Air flow rates of venting layers may be variable because of pressure losses in sand and gravel and interior grade beams, if present. However, the distribution of air flow and pressures has been shown to be relatively uniform for aerated subfloors (Hers and Hood, 2012).

Active Venting without Barrier – Crack Ratio Varied: For this scenario, Q_{vent} was equal to 1 L/min and the crack ratio was varied over two orders of magnitude. The reduction factor varied from 93 to 9300 (**Figure 2**) indicating crack ratio has a potentially significant influence on vapour intrusion for this case. The implication of the modelling is that to improve efficiency of venting, it is important to seal the building foundation through, for example, caulking of cracks or through use of a geomembrane liner. Because the primary purpose of the liner is to improve efficiency of active venting (and not to reduce chemical diffusion), liners that are used as water vapour retarders (e.g., ASTM 1745 Class C) are considered an acceptable option for this application.

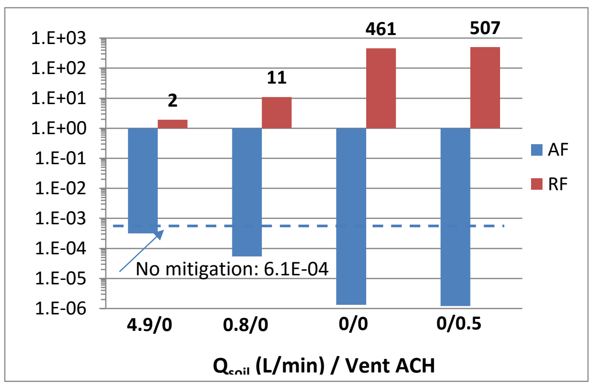

Figure 1: Modelling Results for Passive Venting Case

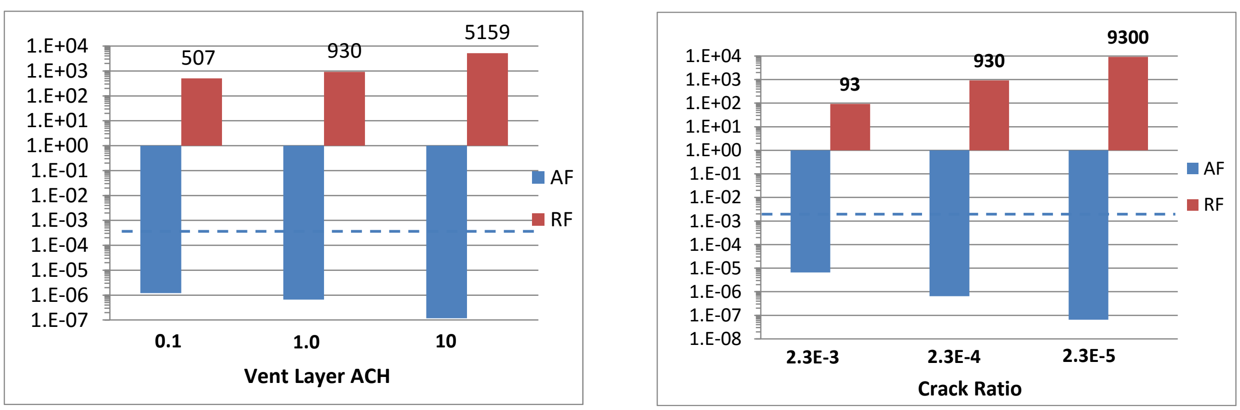

Figure 2: Modelling Results for Active Venting Cases

5. SOIL VAPOUR INTRUSION MITIGATION DESIGN AND MONITORING

Design factors that typical should be considered include whether an existing or future building is being mitigated, the building characteristics and the mitigation target (e.g., as determined by the exceedance ratio, which is the measured or predicted indoor air concentration divided by the acceptable air concentration). In some cases, climate and weather conditions and preferential pathways such as sewers may be important. Key performance factors and measures that may be implemented to optimize and improve sustainability of venting systems are summarized in **Table 6**. For active venting systems, the typical criteria for pressure is a minimum of 6 to 9 Pa negative pressure in the venting layer (ASTM 2121). We note that there is recent research that suggests acceptable performance with smaller pressure differences (Lutes et al. 2015) or an approach where the venting system is designed based on the VOC mass flux (McAlary et al. 2011). Active fans should be sized sustainably to meet targets while minimizing electrical cost and energy cost associated with drawing of conditioned air from the building into the subslab venting layer (Moorman 2009). While typically not an issue for larger buildings, fans should be sized to avoid back-drafting.

Table 6: Performance Factors and Measures for Optimization and Improved Sustainability

Passive Venting	**Active Venting**
Performance Factors	
Building design such as height, foundation, interior grade beams, HVAC design, utility penetrations and pathways will influence both passive and active design and performance	
Pressure gradients and flow in venting layer are variable	Pressure gradients and flow in venting layer can be controlled, only small ΔP is required for mitigation
Convection may enhance venting during the heating season but there is the potential for reverse vent stack effect during warm weather	System design should take into consideration performance during cold weather to counter greater building stack effect
Continuous leak free barrier is required to reduce soil gas diffusion and advection into the building	Sealed foundation and/or a liner to improve efficiency of venting is desirable where possible
Measures for Optimization and Improved Sustainability	
Venting layer consisting of aerated floor or very high permeability gravel layer	Venting layer consisting of aerated floor
Number of vent risers function of venting layer design and climate (1 riser per 200-500 m^2 may be reasonable)	With aerated floor, typically small number of vent risers required; can be designed using quantitative tools
Important to minimize frictional losses in pipes; diameter of vent riser should be greater than pipe lateral; cross-transfer pipes (e.g., 1 per 1 to 3 lineal m) should be installed through grade beams	Frictional losses can be quantified and pipe size can be designed using quantitative tools; cross-transfer pipes (e.g., 1 per 1 to 3 lineal m) should be installed through grade beams
Locating vent stack in heated building or using heat absorbent materials outdoors	Location of vent stack less important
Performance can be improved through wind turbines but depends on climate, site setting and is temporally variable	Acceptable performance can usually be achieved with small, low power radon-type fans

Note: For methane, additional considerations include intrinsically safe equipment and methane monitoring devices.

Available published guidance on monitoring of soil vapour mitigation systems is relatively limited. New Jersey DEP (2013) requires initial commissioning testing of indoor air quality and then a minimum of one additional monitoring event of indoor air quality conducted during the heating season, and physical tests (pressure and flow) for the first year on a quarterly basis and on an annual basis thereafter. The California DTSC (2011) indicates soil vapour mitigation systems may be either passive or active systems. For passive subslab venting systems, seasonal indoor air monitoring is recommended (twice a year) for the first three years or until there is consistent verification that the mitigation system is meeting established indoor air performance measures. For SSD systems, a lesser frequency of indoor air monitoring is potentially acceptable because of monitoring of active depressurization, but no specific recommendation for frequency is provided. The DTSC (2011) guidance acknowledges the significant challenge associated with indoor air monitoring because of the potential confounding influence of background contaminants.

A new approach for monitoring is proposed that is based on mitigation scenario and design and an exceedance ratio concept (**Tables 7** and **8**). A monitoring approach is linked to anticipated performance and required reduction in vapour intrusion and is considered more efficient than previous conventional approaches. The exceedance ratio thresholds of A, B, and C are based on the empirical data review and modelling conducted for this study and are nominally proposed as A equal to 5, B equal to 200 and C equal to 100. Given the certainty in the data, future adjustment of these values may be warranted.

The monitoring approach in **Table 8** is tied to the exceedance ratio scenario. For the low exceedance ratio scenario, limited or possibly no monitoring of indoor air concentrations may be warranted subject to the design and monitoring requirements described below. Monitoring of subslab vapour should typically be considered to confirm mitigation performance, which avoids potential background issues associated with indoor air data. We note that newly constructed plastic piping, caulking and certain membranes could also initially result in off-gassing and elevated VOC concentrations in subslab vapour. While detections of VOCs in subslab vents would not be unexpected in the longer-term; the key factor is whether VOCs are being adequately vented to the outdoor air. To evaluate performance, measured subslab vapour concentrations can be compared to subslab vapour criteria derived using generic regulatory attenuation factors for subslab vapour to indoor air transport or site-specific factors if less conservative criteria are warranted. For the high exceedance ratio scenario, indoor air chemistry monitoring is considered required to confirm that the mitigation system is functioning as expected.

The above framework (particularly if no indoor air monitoring is conducted) requires that mitigation systems be appropriately designed, constructed according to specification, and operated, maintained and monitored. Some factors and performance requirements are identified in this paper, but additional guidance is warranted. For active systems, initial commissioning testing confirming pressure extension below the building is essential, and continuous monitoring of pressures with alarm or notification if the system inadvertently stops functioning is recommended. Pressure data obtained should be interpreted with respect to performance criteria. For passive systems, monitoring of pressures and air flows is also recommended, but further work is needed to define performance criteria. For passive systems, designs that promote venting through the stack effect through use of aerated subfloors or very high permeability gravel (to reduce frictional losses) and stacks located inside buildings or using heat absorbent materials (if outside and south facing) are recommended. Passive venting systems should be designed such that they can be readily converted to active systems, if warranted, and appropriately tested during system commissioning.

Table 7: Soil Vapour Mitigation Exceedance Ratio Framework

Scenario	Building	Exceedance Ratio
Existing Building	Active Venting - SSD	Low < A High > A
Future Building	Active Venting – Liner Optional	Low < B High > B
Future Building	Passive Venting – Barrier Required	Low < C High > C

Table 8: Example Soil Vapour Monitoring Framework

Exceedance Scenario	Subslab Vapour Chemistry	Indoor Air Chemistry
Low	**Recommended** (commissioning + bi-annual for 1 yr)	**Optional**
High	**Recommended** (typically at frequency of indoor air monitoring)	**Required** (commissioning , then bi-annual x 1 yr; then 3rd and 5th yr

Note: An increased monitoring frequency may be warranted for developmental toxicants including indoor air monitoring.

6. CONCLUSIONS

A comprehensive empirical review of data on the performance of active and passive venting systems for soil vapour mitigation was completed. The performance of passive venting systems are variable in terms of venting air flow rates and pressures. Because of the potential for depressurized buildings and/or reverse vent stack effect, for passive venting systems a continuous leak free barrier that reduces the potential for soil gas diffusion and advection is essential. The performance of active venting systems can be more readily controlled and quantified based on design principles as supported by the results of modelling presented here. For both passive and active venting systems improved efficiency in venting can be achieved through aerated subfloors. A monitoring framework that is robust but efficient and sustainable is presented that incorporates a concentration exceedance factor concept and type of mitigation system. Further research is needed to evaluate the efficiency of passive venting including use of wind turbines.

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