TECHNICAL REPORT

CPM Test Guidelines: Use of Controlled Pressure Method Testing for Vapor Intrusion Pathway Assessment

ESTCP Project ER-201501

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This document provides background information and recommendations for practitioners who are planning to use controlled pressure method (CPM) testing for vapor intrusion (VI) pathway assessment. CPM testing is also referred to as “building pressure cycling” and “building pressure control” testing. The recommendations, based on CPM study results published in peer-reviewed journals and ESTCP reports, are intended to be used as a starting point for the design of sitespecific CPM test plans. It is assumed that practitioners are familiar with vapor intrusion and have a familiarity with indoor-air-sample collection and measurement of air flowrates and pressure differentials.

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ACRONYMS AND ABBREVIATIONS

CPM	Controlled Pressure Method
ESTCP	Environmental Security Technology Certification Program
HVAC	Heating, Ventilation and Air Conditioning
NAPL	Non-Aqueous Phase Liquid
QA	Quality Assurance
SERDP	Strategic Environmental Research and Development Program
SEED	SERDP Exploratory Development
SSD	Sub-slab depressurization
VI	Vapor Intrusion

USE OF CONTROLLED PRESSURE METHOD TESTING FOR VAPOR INTRUSION PATHWAY ASSESSMENT

1.0 INTRODUCTION

This document provides background information and recommendations for practitioners who are planning to use controlled pressure method (CPM) testing for vapor intrusion (VI) pathway assessment. CPM testing is also referred to as "building pressure cycling" and "building pressure control" testing. The recommendations, based on CPM study results published in peer-reviewed journals and ESTCP reports, are intended to be used as a starting point for the design of site-specific CPM test plans. It is assumed that practitioners are familiar with vapor intrusion and have a familiarity with indoor-air-sample collection and measurement of air flowrates and pressure differentials.

1.1 BACKGROUND – WHY CONDUCT A CPM TEST

CPM testing is a building-specific diagnostic tool for vapor-intrusion pathway assessment and is applicable to residential and industrial buildings. CPM testing can be used to rapidly determine if VI is or is not of concern in a building that has been identified as having the potential for adverse VI impacts because of its proximity to subsurface contamination in soils, groundwater, or utilities. For many years, the concept has been used for radon intrusion testing (e.g., Froňka et al. 2005, Ringer et al. 2005, Collignan et al. 2012, 2014). It was validated for use for volatile non-radiologic contaminant VI in ESTCP Research Project ER-200707 (McHugh et al. 2012) and the Holton et al. (2015) multi-year SERDP study that compared CPM results against VI impacts under natural conditions.

CPM testing is attractive relative to other building-specific VI pathway test options (e.g., sub-slab soil gas sampling, prolonged indoor air monitoring, etc.), because one to two days of CPM testing can provide:

- a measure of the short-term maximum, worst-case indoor air concentration that might occur due to vapor intrusion at any time in the future under natural conditions; this is predicated on the assumption that, in the future, there are no significant changes to the building (e.g., addition of new piping connections to or through the foundation) or vapor source (e.g., as might happen if the groundwater table rises or falls and submerges or exposes a NAPL source zone),
- an answer to the question as to whether or not a measured indoor air impact is actually the result of VI or instead caused by indoor vapor sources,
- a determination of the VI pathways (e.g., those shown in Figure 1 below), if any, that are significant contributors to indoor air impacts, and
- a much more confident assessment of potential VI impact; for example, unlike occasional daily indoor air testing under natural conditions, CPM testing is extremely unlikely to produce false-negative results (Holton et al. 2015).

With respect to the last bullet above, CPM testing is much quicker and more definitive than relying on multi-season, daily indoor air sampling for VI pathway assessment. Research at a well-instrumented house showed that, unlike indoor air concentrations that varied significantly daily and seasonally under natural conditions, CPM test results (both vapor intrusion rates and concentrations) were relatively constant and not dependent on weather or the day or season of application. In addition, the indoor air concentrations during CPM testing were similar to the short-term maximum measured under natural conditions and were one to two orders of magnitude greater than the long-term time-average value under natural conditions (Holton et al. 2013, 2015). As such, a single one- to two-day CPM test is generally sufficient for VI pathway assessment purposes and will not produce the false-negative results that are possible with conventional indoor air sampling plans (Holton et al. 2013).

1.2 CONCLUSIONS AFTER CONDUCTING A CPM TEST

After conducting a CPM test and considering other site data and relevant regulatory targets, it might be decided that: a) VI does not pose a significant risk to the building occupant's health and no further testing is required, b) additional indoor air monitoring is necessary, for example using multi-week passive samplers, or c) mitigation is necessary. In the case of the latter, CPM test data are valuable to mitigation system design.

2.0 VI PATHWAY CONCEPTUALIZATION AND CPM TEST OVERVIEW

Before conducting CPM tests and interpreting the data, it is important to understand how VI is conceptualized and to recognize that VI behavior and indoor air impacts can be dependent on building-specific features that are not usually known, but might be revealed through CPM test data analysis.

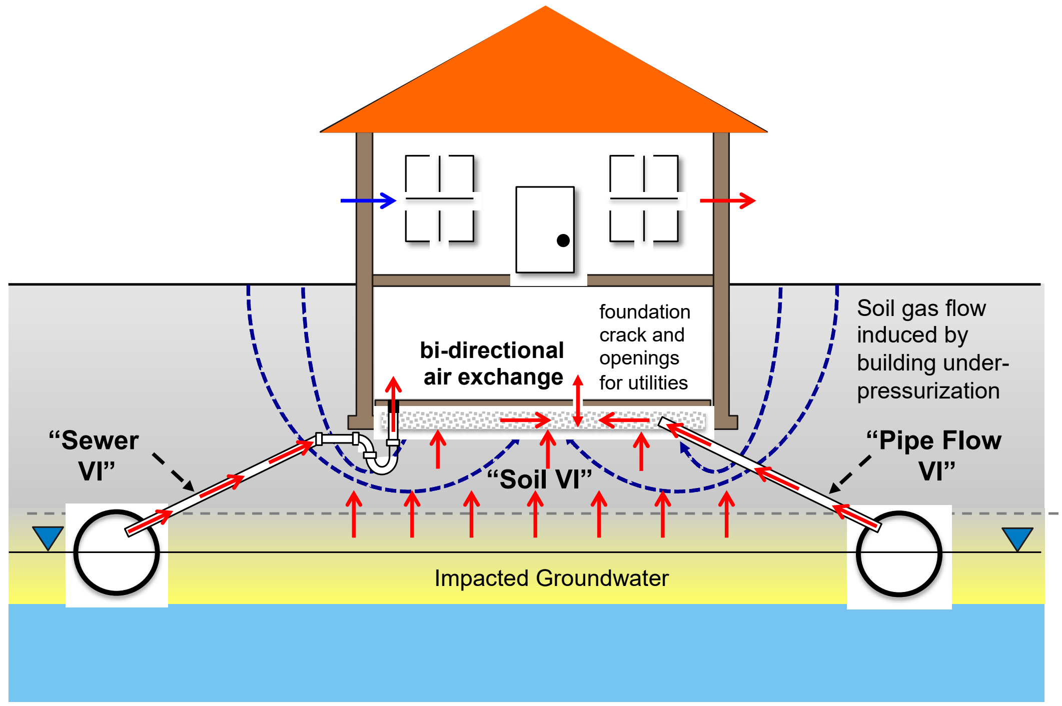

Figure 1: Conceptualization of possible vapor intrusion pathways.

With respect to VI pathway conceptualization, chemical vapors can move from subsurface sources, travel through the soil matrix, and eventually enter an overlying or adjacent building via foundation cracks or other openings; this VI mechanism was named "soil VI" by Guo et al. (2015). VI can also result from vapor transport through subsurface conduits and piping networks, directly to indoor air; this VI mechanism was named "sewer VI" by Guo et al. (2015), although sewers are not the only types of conduits that can facilitate vapor intrusion directly to indoor air. VI can also result from vapor transport through subsurface piping networks to the sub-slab soil region and then through the foundation into indoor air; this process was named "pipe flow VI" by Guo et al. (2015). The "soil VI", "sewer VI", and "pipe flow VI" pathways are depicted conceptually in Figure 1.

Under natural conditions, indoor-outdoor and indoor-sub-slab soil gas pressure differences occur due to wind, indoor-outdoor temperature differences, building ventilation system operation, and other environmental and building use factors. When its indoor pressure is less than the local atmospheric and sub-slab soil gas pressures, a building is said to be "under-pressurized." That condition will cause outdoor air and soil gas to be drawn into the building. Conversely, when its indoor pressure is greater than the local atmospheric and the sub-soil soil gas pressures, a building is said to be "over-pressurized," and that condition will cause indoor air to flow to the atmosphere and down into the soil gas or a sub-floor crawl space area. The extent to which a building is naturally under- or over-pressurized varies with time; indoor-outdoor and indoor-sub-slab soil gas pressure difference measurements under natural conditions typically show rapid (seconds) short-term pressure difference fluctuations about long-term daily and seasonally changing averages (e.g., SERDP ER-1686 Final Report, Appendix A, Figure A.51 (Page 211 of 248); SERDP 2016). It is that time-dependent pressure difference dynamic that causes VI impacts to vary significantly with time in some buildings.

CPM tests overcome this natural variability in pressure difference by temporarily creating a constant indoor-outdoor pressure difference through use of an exhaust fan mounted in a door or window as shown conceptually in Figures 2 and 3. In larger buildings, it might be possible to accomplish the same result through manipulation of the building HVAC system.

A "negative pressure difference" CPM test (Figure 2), in which air is exhausted from a building, induces soil gas and subsurface vapor movement toward the building, is similar to what happens when natural conditions (e.g., wind, indoor-outdoor temperature difference) create an under-pressurized building condition. Conversely, the "positive pressure difference" CPM test, shown in Figure 3, suppresses vapor entry. By conducting both negative pressure difference and positive pressure difference tests, one can directly measure short-term maximum (worst-case) VI impacts likely to happen under natural conditions, and identify the contributions, if any, from indoor air sources. As was seen in the Holton et al. (2013, 2015) study, CPM test results will also likely exceed long-term time-average impacts under natural conditions by one or more orders of magnitude – assuming no significant changes to the building (e.g., addition of new piping connections to or through the foundation) or vapor source (e.g., as might happen if the groundwater table rises/falls and submerges/exposes a NAPL source zone) occur in the future.

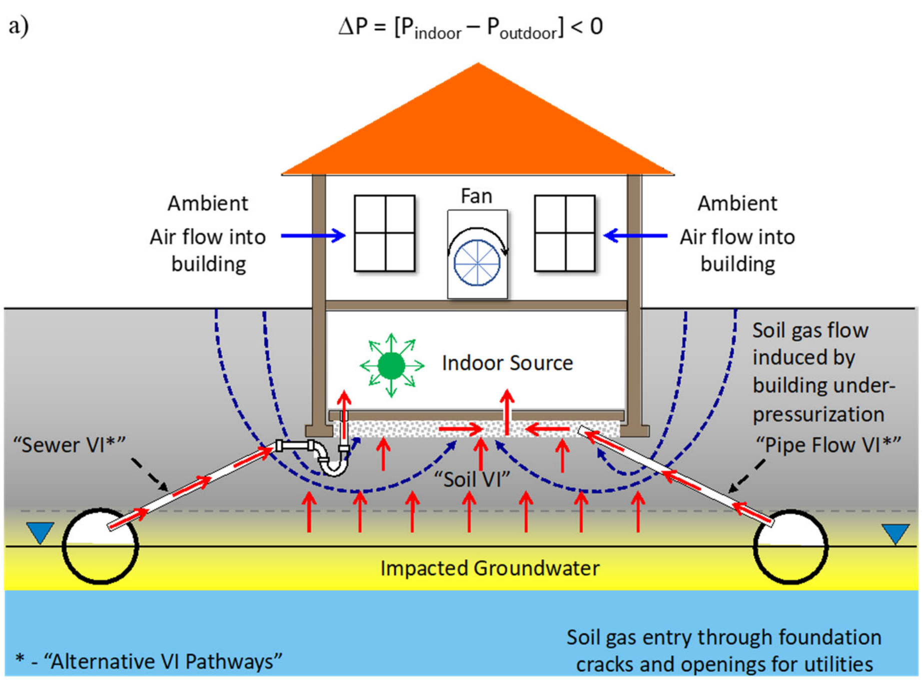

Figure 2: CPM test schematic of negative pressure difference

b)

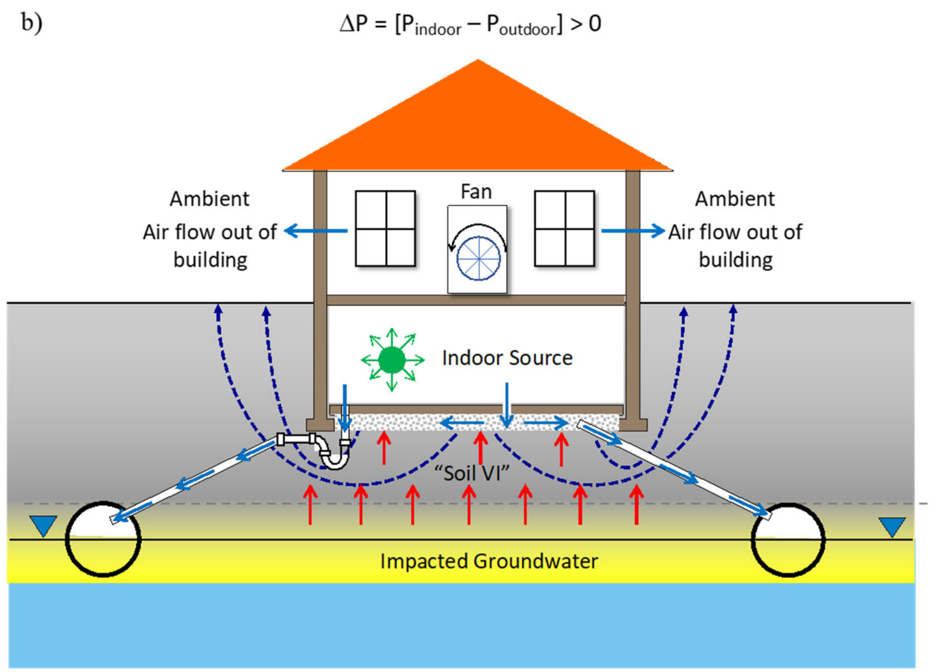

Figure 3: CPM test schematic of positive pressure difference test.

3.0 USE OF CPM TESTING FOR BUILDING-SPECIFIC VI PATHWAY ASSESSMENT

Figure 4 presents the high-level logic and recommended sequence of activities and decisions associated with CPM test application and data analysis. The logic requires little explanation, but a few components deserve some discussion.

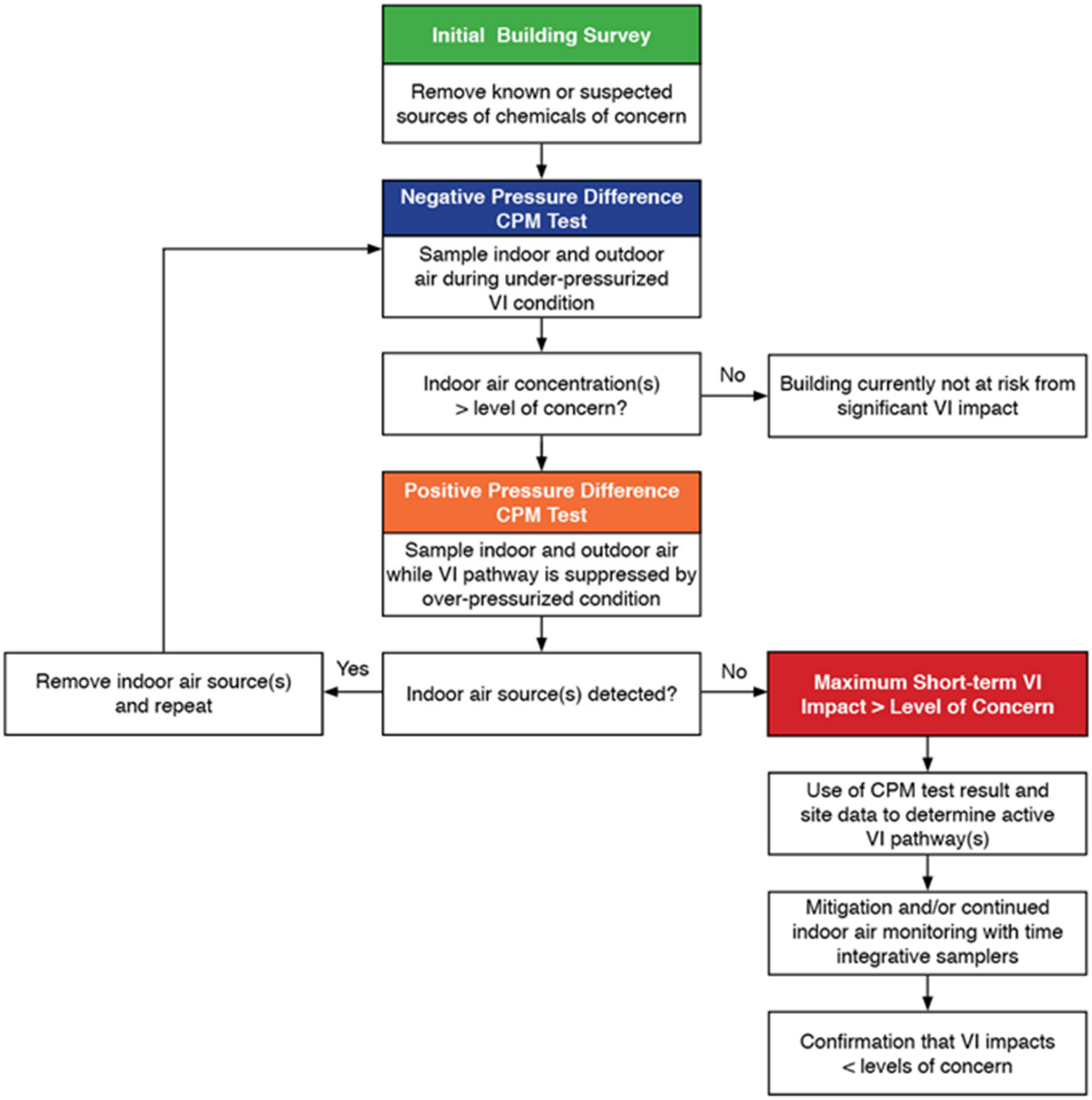

Figure 4: Logic associated with CPM test application and decision-making.

First, with respect to decision-making components in this figure, selecting chemical-specific levels of concern is a key and often a negotiated step involving input from regulators, stakeholders, and responsible parties. For occupied buildings, protection of human health is a primary concern, particularly for contaminants that may have toxic effects after short-term exposures. In addition to reviewing local and regional risk-based screening levels, ambient background concentrations should be considered, since incremental risk or impact due to VI – under natural or CPM test conditions – can only be detected and quantified when VI results in indoor concentrations above ambient background levels.

It is also important to consider the fact that negative pressure difference CPM tests represent short-term maximum, worst-case conditions. For example, at the Holton et al. (2013, 2015) study house, indoor air concentrations during CPM testing were similar to the maximum hourly and daily indoor air concentration observed under natural conditions over a multi-year period, and they were also more than 10 times greater than the long-term average indoor air concentration observed under natural conditions.

Second, although Figure 3 shows evaluation of negative pressure difference CPM test results before proceeding, if necessary, to positive pressure difference testing – practical considerations (e.g., mobilization cost, building access restrictions, etc.) might dictate conducting a positive pressure difference test immediately following a negative pressure test before knowing the negative pressure test results. This could be the case when vapor samples are sent for analysis to remote laboratories with multi-week delays in obtaining the results. This consideration illustrates the value of employing a mobile analytical lab or mobile analytical equipment for air sample analysis during CPM testing for a rapid turn-around of data. DoD users should be cognizant that only laboratories with DoD Environmental Laboratory Accreditation (ELAP) can be utilized for obtaining data that are used for definitive decision-making. If a mobile lab is used and is not ELAP accredited, or mobile analytical equipment is used, users should consider collecting split samples that are analyzed both on-site and at an accredited fixed lab to validate results of samples analyzed at the test site.

Finally, use of CPM test data with other site data to determine active VI pathways before deciding to proceed with mitigation and/or continued indoor air monitoring is discussed below after presentation of the recommended CPM test design guidelines.

4.0 RECOMMENDED CPM TEST DESIGN GUIDELINES

Guo et al. (2020) conducted a systematic study of CPM test design specifics in a well-instrumented house, looking at factors such as blower door placement, blower flowrates, use of fans for indoor air mixing, and CPM test duration. From that, they developed proposed CPM test guidelines for both negative- and positive-pressure-difference CPM tests and then demonstrated their application at four residential and four industrial buildings, including ones where vapor intrusion did and did not pose an actionable human health risk (ESTCP ER201501 Final Report, 2020). Those guidelines are presented below in Tables 1 and 2. It is possible that other CPM test conditions might be sufficient (e.g., different pressure differentials and test durations), but that would need to be supported with transient concentration versus time data that demonstrates reaching near-steady conditions under those conditions.

The appendix provides practical step-by-step guidelines for conducting CPM tests.

4.1 KEY EQUIPMENT SELECTION

Key equipment for CPM tests include blower doors, differential pressure transducers, fans, and air samplers. A few comments on these are included below:

Blower door panels: A commercial "blower door panel," such as those used for HVAC leak testing, is recommended for CPM testing. These usually have an adjustable rigid frame covered with airimpermeable cloth or rigid panels that can be sized to fit tightly in an open doorway. The panel also has elasticized cutouts to hold one or more blowers (typically brand specific).

Blower capacity needs to be sized to manage a minimum cross-envelope differential pressure of 10 Pa and >9 building volumes of flow within the selected test period (likely to be eight hours for residential tests for practical reasons and could be longer for industrial buildings). A single commercial blower door panel is generally sufficient for a typical residential house and two or more blower panels with multiple fans each may be needed for industrial buildings where manipulation of the HVAC system cannot be used to create the desired pressure difference condition. The >9 building volume criterion comes from empirical analysis of test results (e.g., Guo et al. 2020) and is not based on any assumptions related to the extent of mixing within a building.

Pressure monitoring equipment: Real-time differential pressure monitoring with a minimum resolution of 1 Pa is necessary for CPM testing. Commercial HVAC leak testing blower door equipment often includes a control module that allows control of either the fan speed or the indoor-outdoor pressure difference and displays and logs the indoor-outdoor pressure difference and fan flowrate. If not using a commercial blower door unit, a real-time differential pressure monitoring instrument is needed. For large and complex industrial buildings, additional indoor-outdoor pressure difference monitoring locations may be used to verify achievement of the design indoor-outdoor pressure differential throughout the building.

Use of fans for indoor air mixing: Portable, vertically pivoting, industrial type fans – usually available from the hardware store – are required for air mixing in front of the blower intake and in rooms to be sampled. Depending on room size, multiple fans may be necessary.

Air sampling equipment: Air samplers, such as Summa canisters and/or active sorbent tube samplers for remote laboratory analysis, and/or syringes or Tedlar bags as needed for on-site analysis are necessary. The clients (e.g., regulatory agencies and/or responsible parties) may have specific sampling method requirements for different types of data. For example, on-site analysis might be acceptable for on-site screening and test condition validation purposes (e.g., verifying near-steady conditions have been reached), but Summa canister sampling with fixed-lab analysis might be required for the final steady-state blower intake air sample.

Photos of a typical CPM test blower-door test set-up are presented in Figure 5.

Table 3: Test Design Guidelines for Negative Pressure Difference CPM Tests.

Negative Pressure Difference CPM Tests	
Exhaust Fan Location	Install fan in any convenient location (results were unaffected by placement in the Guo et al. (2020) research study). Position the fan to exhaust air from the structure. See also ASTM E779 and ISO 9972 for pressure monitoring and blower installation guidance.
Exhaust Fan Operating Conditions	Adjust the exhaust fan flowrate to achieve a consistent negative indoor – outdoor pressure difference in the range -10 Pa to -15 Pa during the test. Within that pressure difference range, increasing the fan flowrate will decrease the time needed to achieve the required minimum 9 indoor air exchanges.
Test Duration [a]	Conduct negative pressure difference CPM tests for at least 9 air exchanges before indoor air sampling; this will require a time equal to 9 times Building Volume/Fan Flowrate. Alternatively, the CPM test duration can be validated with time-dependent room-specific air sampling and analysis.
Operating Conditions Monitoring [b]	The following capabilities are commonly instrumented on commercially available blower door setups: • Indoor – outdoor pressure difference. It is recommended that the outdoor pressure reference point connects to open-ended tubing running from all exterior sides of the building. • Exhaust fan flowrate (flow-calibrated equipment is preferred; tracer testing is an alternative option for flowrate measures).
Air Sample Collection Locations [c, d, e] (after 9 air exchanges)	Relevant guidance for sample collection procedures and specific sampling techniques should be reviewed. The following sampling locations are recommended: • One or more grab samples collected near the fan intake with active floor-fan mixing near the fan intake • One or more outdoor grab or test duration time-integrated air samples • One or more samples collected from pre-selected rooms, using active floor-fan mixing in each room during sample collection.
Data Evaluation	Concentrations in vapor samples collected near the fan intake are expected to be representative of maximum short-term indoor air concentrations under natural conditions. They are also expected to be greater than long-term average indoor air concentrations under natural conditions. If the observed concentrations are greater than levels of concern and greater than outdoor air concentrations, it is important to note that this could be the result of VI, indoor sources, or a combination of the two. Positive pressure difference testing should differentiate between the two. Area-specific or in-room sampling results may provide valuable insight to VI entry and indoor source release points.

Other	All doors, windows, and vents should be closed during testing to minimize the potential for exaggerated dilution of VI by indoor air. CPM test results can be used to assess if alternate VI pathways might be contributing to significant indoor air impacts as discussed in Guo et al. (2015).

Note: These guidelines are updated from Guo et al. (2020).
[1] If desired, the negative pressure difference CPM test duration can be validated by collecting and analyzing blower intake air samples with time, and the positive pressure difference CPM test duration can be validated by collecting and analyzing room-specific air samples with time.
[2] For large and complex industrial buildings, additional indoor-outdoor pressure difference monitoring locations may be needed to verify achievement of the design indoor-outdoor pressure differential throughout the building.
[3] Clients may have specific sampling and analysis requirements for different types of data. For example, collection in syringes or Tedlar bags followed by on-site analysis might be acceptable for on-site screening and test condition validation purposes (e.g., verifying near-steady conditions have been reached), while Summa canister sampling with remote fixed-lab analysis might be required for the final steady-state air samples.
[4] Samples collected from individual rooms can provide useful insight to vapor intrusion locations when VI is detected. Rooms are selected based on consideration of their use and the potential that they might be vapor intrusion points.
[5] Field screening vapor detection instruments might also be used to test suspected vapor intrusion points during the negative pressure difference CPM test.

Table 4: Test Design Guidelines for Positive Pressure Difference CPM Tests.

Test Design Guidelines for Positive Pressure Difference CPM Tests	
Fan Location	Install fan in any convenient location (results were unaffected by placement in the Guo et al. (2020) research study). Position the fan to blow ambient air into the structure.
Fan Operating Conditions [a]	Adjust the exhaust fan flowrate to achieve an indoor – outdoor pressure difference in the range +5 Pa to +15 Pa to insure a consistent positive cross-foundation pressure difference during the test.
Test Duration [b]	Conduct positive pressure difference CPM tests for at least 4 air exchanges before indoor air sampling; this will require a time = 4 x Building Volume/Fan Flowrate. Alternatively, the CPM test duration can be validated with time-dependent room-specific air sampling and analysis.
Operating Conditions Monitoring [b]	The following are commonly instrumented on commercially available blower door setups: • Indoor – outdoor pressure difference. It is recommended that the outdoor reference point connects to open-ended tubing running from all exterior sides of the building. • Fan flowrate.

Air Sample Collection Locations [c] (after 4 air exchanges)	Relevant guidance for sample collection procedures and specific sampling techniques should be reviewed. The following sampling locations are essential: • One or more outdoor grab or test duration time-integrated air samples • One or more grab samples collected from each room with active floor-fan mixing in each room during sample collection.
Data Evaluation	Positive pressure difference tests will significantly reduce subsurface VI impacts[6]; therefore, if indoor air concentrations are greater than ambient (outdoor) air concentrations, this indicates contributions from one or more indoor sources that then should be removed before repeating the negative pressure difference CPM test. In-room sampling results will help indicate the locations of indoor source releases. If room-specific results were collected during the negative pressure difference test, these should be compared with positive pressure difference test results. Minimal changes in concentration between the two in rooms with concentrations of concern will suggest the presence of indoor sources in those rooms.
Other	All doors, windows, and vents should be closed during testing.

Note: These guidelines are updated from Guo et al. (2020) and should be conducted only if impact of significance is detected by a negative pressure difference test.

[a] Modeling studies suggest that indoor-outdoor pressure differentials >5 Pa are sufficient to suppress vapor intrusion (e.g., Abreu and Johnson, 2005). Increasing the pressure difference and fan flowrate will decrease the test duration but might also decrease the ability to detect indoor sources due to increased dilution.

[b] If desired, the negative pressure difference CPM test duration can be validated by collecting and analyzing blower intake air samples with time, and the positive pressure difference CPM test duration can be validated by collecting and analyzing room-specific air samples with time.

[c] For large and complex industrial buildings, additional indoor-outdoor pressure difference monitoring locations may be needed to verify achievement of the design indoor-outdoor pressure differential throughout the building.

a)
b)
c)


Figure 5. Photos from an industrial multi-blower (panel a) and residential single blower door (panels b and c) CPM test deployment.

5.0 USE OF CPM TEST DATA WITH OTHER SITE DATA TO IDENTIFY ACTIVE VI PATHWAYS

Should CPM testing reveal potential VI impacts of significance, it will be necessary to decide what response actions are needed (e.g., mitigation, monitoring, etc.). Critical to that decision is development of the best possible VI site conceptual model, as some mitigation approaches are effective for certain VI pathways, but not others. For example, the typical presumptive VI remedy – a sub-slab depressurization system – can protect against soil VI pathway impacts, but may not be effective for sewer VI pathway impacts.

Guo et al. (2015) illustrated the use of site and CPM test data from a study house where an unknown pipe flow VI pathway was detected through data analysis and later confirmed by excavation near the house. Their analysis followed this sequence of steps:

a) Calculation of the measured chemical vapor emission rate, $E_{measured}$ [μg/d], from the house during the negative pressure difference CPM test:

   $E_{measured} = (C_I – C_{outdoor}) \times Q_{blower} \times 1440$ min/d

   where C_I [μg/m^3] is the indoor air concentration measured at the blower intake, $C_{outdoor}$ is the outdoor air concentration, and Q_{blower} is the blower flowrate [m^3/min], both measured toward the end of the negative pressure difference CPM test (after 9 building exchange volumes per Table 1).

b) Estimation of the chemical vapor emission rate associated with the soil VI pathway only, using the USEPA spreadsheet implementation of the Johnson and Ettinger model:

   $E_{estimated} = C_{I,estimated} \times V_B \times E_B$

   where $C_{I,estimated}$ [μg/m^3] is the indoor air concentration estimated in the USEPA spreadsheet, and V_B and E_B are the building volume [m^3] and indoor air exchange rate [1/day], both input to the USEPA spreadsheet implementation of the Johnson and Ettinger model.

c) Comparison of $E_{measured}$ and $E_{estimated}$. When $E_{measured} >> E_{estimated}$, this is an indication of the presence of a significant VI pathway other than the soil VI pathway, or poor site characterization data.

d) Differentiating between pipe flow and sewer VI pathways, if suspected of being present, requires additional testing. For example, one might sample vapors in relevant subsurface piping networks (e.g., sewers and land drains) to confirm that chemicals of concern are present at concentrations greater than what has been detected indoor. If so, then this might be followed by a CPM negative pressure test while also implementing sub-slab depressurization (SSD). If the vapor intrusion (concentrations and intrusion rate) detected during CPM testing alone continue during a dual CPM+SSD test, this is an indication that the dominant VI pathway is via sewer VI. If the vapor intrusion detected during CPM testing alone is significantly reduced during a dual CPM+SSD test, this is an indication that the dominant VI pathway is some combination of pipe flow VI and soil VI.

REFERENCES

Abreu, L. and P.C. Johnson. 2005. Effect of Vapor Source-Building Separation and Building Construction on Soil Vapor Intrusion as Studied with a Three-Dimensional Numerical Model. Environmental Science and Technology. *39*(12). 4550-4561.

Collignan, B.; Lorkowski, C.; Améon, R. Development of a Methodology to Characterize Radon Entry in Dwellings. *Build. Environ.* 2012, *57*, 176–183. https://doi.org/10.1016/j.buildenv.2012.05.002.

Collignan, B.; Powaga, E. Procedure for the Characterization of Radon Potential in Existing Dwellings and to Assess the Annual Average Indoor Radon Concentration. *J. Environ. Radioact.* 2014, *137*, 64–70. https://doi.org/10.1016/j.jenvrad.2014.06.024.

ESTCP. Final Report for Project ER-201501. The VI Diagnosis Toolkit for Assessing Vapor Intrusion Impacts and Selecting Remedies in Neighborhoods and Industrial Buildings Overlying Dissolved Chlorinated Solvent Plumes. Project ER201501. October 2020 (in preparation).

Froňka, A.; Moučka, L. Blower Door Method and Measurement Technology in Radon Diagnosis. *Int. Congr. Ser.* 2005, *1276*, 377–378. https://doi.org/10.1016/j.ics.2004.11.140.

Guo, Y.; Holton, C.; Luo, H.; Dahlen, P.; Gorder, K.; Dettenmaier, E.; Johnson, P. C. Identification of Alternative Vapor Intrusion Pathways Using Controlled Pressure Testing, Soil Gas Monitoring, and Screening Model Calculations. *Environ. Sci. Technol.* 2015, *49* (22), 13472–13482. https://doi.org/10.1021/acs.est.5b03564.

Guo, Y.; Dahlen, P.; Johnson, P. C. Development and Validation of a Controlled Pressure Method Test Protocol for Vapor Intrusion Pathway Assessment. *Environ. Sci. Technol.* 2020 *54* (12), 7117-7125. https://doi.org/10.1021/acs.est.0c00811.

Holton, C.; Guo, Y.; Luo, H.; Dahlen, P.; Gorder, K.; Dettenmaier, E.; Johnson, P. C. Long-Term Evaluation of the Controlled Pressure Method for Assessment of the Vapor Intrusion Pathway. *Environ. Sci. Technol.* 2015, *49* (4), 2091–2098. https://doi.org/10.1021/es5052342.

Holton, C.; Luo, H.; Dahlen, P.; Gorder, K.; Dettenmaier, E.; Johnson, P. C. Temporal Variability of Indoor Air Concentrations under Natural Conditions in a House Overlying a Dilute Chlorinated Solvent Groundwater Plume. *Environ. Sci. Technol.* 2013, *47* (23), 13347–13354. https://doi.org/10.1021/es4024767.

McHugh, T. E.; Beckley, L.; Bailey, D.; Gorder, K.; Dettenmaier, E.; Rivera-Duarte, I.; Brock, S.; MacGregor, I. C. Evaluation of Vapor Intrusion Using Controlled Building Pressure. *Environ. Sci. Technol.* 2012, *46* (9), 4792–4799. https://doi.org/10.1021/es204483g.

McHugh, T.E., Beckley, L. and D. Bailey. 2012. Protocol for Tier 2 Evaulation of Vapor Intrusion at Corrective Action Sites. ESTCP Project ER-200707. https://serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-200707/ER-200707.

Ringer, W.; Kaineder, H.; Maringer, F. J.; Kindl, P. Determination of the Radon Potential of a

Building by a Controlled Depressurisation Technique (RACODE). *Radioact. Environ.* 2005, *7* (C), 221–231. https://doi.org/10.1016/S1569-4860(04)07025-1.

SERDP. 2016. Final Report for Project ER-1686: Integrated Field-Scale, Lab-Scale, and Modeling Studies for Improving Our Ability to Assess the Groundwater to Indoor Air Pathway at Chlorinated Solvent-Impacted Groundwater Sites. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1686/ER-1686.

Appendix

Practical Considerations for Conducting CPM Tests

Safety

Proper safety precautions should be observed when conducting CPM testing. At least two personnel are recommended for CPM testing.

Time Planning for CPM Testing

When considering setup and takedown and the time required to achieve the necessary air exchange volumes, it will likely take one full day for negative pressure testing and another day for positive pressure testing for residential buildings. Industrial buildings may take similar times or longer, depending on their complexity and the extent to which the HVAC system might be manipulated to achieve the desired pressure difference condition. Negative pressure testing is the most time intensive aspect of CPM testing as it requires a minimum of 9 building volumes of air flow (see Table 1). For typical blower exhaust flowrates necessary to achieve the minimum pressure of -10 Pa, a full day is necessary. Increasing the blower flowrate during negative pressure testing is a viable option to ensure the test can be performed in a single day.

Presence of Building Occupants During CPM Testing

Negative pressure testing is designed to draw contaminants into the test structure. As such, contaminant exposure is a risk if building occupants are present. Usually building occupants are not present during CPM testing.

Pre-Test Activities

The preparation of a work plan that describes the CPM test design and sampling and analysis procedures should be reviewed with regulators, stakeholders, and responsible parties as a part of the pre-test activities. Pre-test activities might also include use of portable real-time vapor monitoring equipment to identify indoor air sources.

Pre-test communication with homeowners, building managers, occupants, and/or anyone who needs indoor access during the test should occur, and those discussions should include following topics:

- CPM basics and activities to be conducted by testing personal.
- Activity restrictions for anyone present during the test, such as creating unintentional building openings. With respect to building entrance and egress, anyone present should be asked to refrain from entrance and egress during the test, and if it is necessary, to make transitions as quickly as possible and to leave doors in the position they were found (closed or ajar).
- The homeowner, building manager, and/or occupants should be interviewed to identify locations where commercial products are stored and used and identify other activities (e.g., gun-cleaning or equipment de-greasing products) that could possibly contribute vapors to indoor air. If any are identified, those should be removed prior to CPM testing.

Survey the interior spaces for their size, use and occupancy, and any obvious vapor intrusion entry points. Large and complex buildings may warrant isolating and testing areas that may differ in their use and vapor intrusion potential. Whole-building testing may be done in addition to area-specific testing. Total building size, ventilation networks, HVAC system operation, etc. should be determined.

Ensure that power is available for each blower door installation. Also, it is good to power each blower on separate circuits, as single blowers and associated equipment may require up to 15 amps per unit, and 20 amps in some cases.

Ensure that all doors inside the structure (including doors to closets, pantries, storerooms, etc.) are open for effective airflow throughout the structure.

Survey the structure to identify any large vents or exhaust equipment that might affect building pressurization. Seal or close-off any vents or exhaust equipment identified.

Turn off HVAC system.

Turn off the vapor recovery system (radon and/or hydrocarbon mitigation system) if one exists.

Blower Door, Blower, and Pressure Monitoring Installation

Identify blower door installation location(s). A suitable exterior opening through the building envelope is needed (e.g. door or window) for blower door installation. The opening should be in an area "connected" with the rest of the structure via open doorways. Note that a doorway into an enclosed garage is not a suitable location for blower door installation since the garage is "connected" to the rest of the structure and would not allow ventilation to the atmosphere.

If the garage is an integral part of the structure, external doors should be closed and it should be treated as any other interior room for testing purposes.

Choose a location in which the blower intake and exhaust is unimpeded both inside and outside the structure. Weather protection should also be considered. In some cases, it may be desirable to use large diameter tubing or flexible ducting to direct the fan exhaust some distance away from the house.

Install the blower door into the selected building opening as per manufacturer's instructions and ensure that any gaps are sealed. For negative pressure testing, install the blower/fan to blow indoor air out of the structure. For positive pressure testing, install the blower/fan to blow outdoor air into the structure.

Install cross-building envelope differential pressure monitoring reference points. The indoor pressure monitoring point should be at least 3m (10 ft) away from and out of the direct path of the blower exhaust. If the structure is open throughout its interior as is required for CPM testing, only a single indoor reference point is necessary unless the building layout (e.g., a long hallway between the blower door and large rooms) or high leakage rates through the building envelope create the need for additional monitoring points. For larger buildings with compartmentalized interior occupied spaces, consider measuring the indoor-outdoor pressure differences for multiple locations to confirm maximum worst-case vapor intrusion conditions exist throughout the building.

The outdoor pressure-monitoring point should be at least 3 m (10 ft) away from and out of the direct path of the blower exhaust. A composite outdoor reference (composite pressure reference with monitoring from multiple sides/aspects of the building) is recommended as it effectively reduces the variability associated with wind loading or short-term gusts of wind. Pressure monitoring should avoid areas of air turbulence including building corners, alcoves, or near the eves or roofline. Placing porous foam rubber around the pressure monitoring tubing opening can help attenuate the pressure fluctuations caused by localized turbulence or wind speed changes.

Ambient (Outdoor) Air Sample Collection

Outdoor air sample(s) should be collected outside the building envelope prior to and during CPM testing, preferably using the same equipment and procedures used for the indoor air sample collection during the CPM test. Individual grab samples from two or more locations or a spatial composite air sample from the perimeter of the structure are recommended, and ideally the external sample is collected over the duration of the CPM test.

Data Quality Objectives, Sampling, and Analytical Methods

Data quality objectives and sampling and analysis methods should be provided in the project work plan. This will ensure the methods for sampling and analysis meet data quality requirements for each phase of testing. Planned and potential uses of the data and the data quality requirement of each use should be described. Target contaminants and corresponding analytical goals should be provided in the work plan. Field duplicates, blanks, and other quality assurance samples should be described. Inter-method sampling for verification and field calibration may be needed for certain sampling methods.

For data that are going to be used as lines of evidence in VI health risk assessment and/or risk-based decisions, definitive, certified methods should be used (sampling and analysis).

Controlled Building Pressure Testing Steps

Negative Pressure Difference Testing:

1. Estimate the interior volume to be tested ($V_{building}$).

2. Initiate blower/fan operation and set the speed to obtain a minimum indoor-outdoor pressure differential of approximately -10 Pa and a flowrate capable of achieving >9 building volumes within the allotted test time.

3. Measure the blower flowrate (Q_{blower}) and determine the minimum period of operation ($T_{ss,neg}$) to achieve steady conditions. $T_{ss,neg}$ is defined as the time to reach 9 air exchanges ($T_{ss,neg} = 9 \text{ x } V_{building}/Q_{blower}$).

4. CPM testing start time is defined as the time that cross-envelope pressure differential stabilizes (less than 20% pressure fluctuation).

5. Continue blower operation until $T_{ss,neg}$ is reached, or on-site analytical results indicate concentration equilibrium has been achieved.

6. Survey the building after startup and periodically during the CPM test to ensure all doors are positioned in the manner intended. Frequently doors will open/close as a result of blower operation and/or occupants may open/close doors and neglect to reposition them as needed for the test. Rapid changes in indoor-outdoor building pressure are sometimes an indication of the opening/closing of doors and windows.

7. Install an air sampler approximately 30 cm (1 ft) from intake face of the blower such that it is centered both vertically and horizontally in front of the blower intake.

8. Install air mixing fans in the same room as the blower and orient fans to optimize air mixing within that room and near the blower intake. Air mixing fans are necessary to minimize spatial variability and to ensure an accurate assessment of air concentration.

9. If on-site analytical is utilized, collect samples periodically (i.e. at each building air exchange) from in front of the blower intake to verify that steady conditions are achieved. Consider collecting co-located quality assurance samples for laboratory analysis to evaluate the accuracy of the on-site analytical methods. The quantity and location of these samples should be discussed and agreed upon with regulatory agencies prior to testing.

10. If on-site analytical is not applicable, air samples should be collected from in front of the blower intake after $T_{ss,neg}$ is reached. More than one sample would be helpful for quality assurance purposes. Consider collecting three samples, one after each of eight, nine, and 10 exchange volumes.

11. Label all samples and send to lab for analysis. The label should include necessary information including sampling time and location.

12. Samples collected from individual rooms to help identify VI entry points that are associated with indoor vapor sources should be collected after $T_{ss,neg}$ is reached.

As a general note, if data are to be used for health risk-based decisions in addition to VI pathway identification, the sampling and analytical methods need to provide data of adequate quality (definitive chemical identification and accurate air concentrations). In some cases, definitive methods may be used as a confirmatory method for a subset of samples collected (e.g., grab samples analyzed in the field).

Positive Pressure Difference Testing:

1. Install the blower/fan with the fan reversed so that it blows ambient air into the structure.

2. Initiate blower/fan operation and set the speed to obtain a minimum cross-envelope pressure differential of approximately +5 to +15 Pa and a flowrate capable of achieving >4 building volumes within the allotted test time.

3. At least one grab sample should be collected in each room and common area of the test building. Prior to sample collection, close the door(s) to the room and mix the air for at least one minute using a portable floor fan, and maintain fan operation during sample collection.

4. Label all samples and send to lab for analysis. The label should include necessary information including sampling time and location.

Post-Test Procedures

Post-test procedures include equipment demobilization and restoring the structure to its condition prior to the test. While equipment demobilization is self-explanatory, restoring the structure to its pre-test condition is not as apparent. Pay attention to the following when restoring the structure to its pre-test condition:

- Removal of tape or covers used to block vents.
- Closing/opening doors as appropriate throughout the structure.
- Turn on HVAC system as appropriate; inspect HVAC and/or water heater pilot lights to ensure they are still operational or re-light as necessary. It is not uncommon that pressure testing creates an abnormal flux of air through the HVAC and/or water heater and extinguishes the pilot.
- Restore operation of VI or radon mitigation system (if present).

Reporting

The field investigation report should include the following:

- <u>Introduction</u>: Identify the objective and context of the investigation program. Provide a description of the test building and relevant information such as contaminant of concern, contaminant source, subsurface concentrations closest to the building, building information, etc. A conceptual site model specific to the site and building should be included.
- <u>Methods:</u> Describe the sampling methods, sampling locations, and rational for location selection. Describe the CPM testing process. Instrument calibration and QA procedures should also be included if on-site analytics are applied.
- <u>Results:</u> Tabulate results and summarize them in time series if applicable. Include applicable measurement limits and uncertainty.
- <u>Data Interpretation:</u> Discuss the results from negative and positive pressure testing processes, and perform the analyses discussed in the main body of this document.
- <u>Appendices:</u> Field notes, laboratory analytical reports, and investigation details should be provided in appendices, as appropriate.