Optimization of Building Pressure Cycling Methods for Vapor Intrusion Studies in Large Buildings

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Executive Summary

This technical memorandum (TM) provides the Department of the Navy's (Navy's) Environmental Restoration Program Remedial Project Managers with information related to building pressure cycling (BPC) methods for conducting vapor intrusion (VI) investigations in buildings typical of Department of Defense (DoD) installations. During a BPC test, a building—or sampling zone within a building—is depressurized with a fan to create conditions that facilitate VI-related migration of subsurface vapors into the sampling zone indoor air. The data can be used to assess temporal variability of volatile organic compound (VOC) concentrations in indoor air, identify potential background sources of VOCs within the sampling zone, or locate potential VI entry points. Under certain conditions, a single mobilization can suffice to either rule out the VI pathway or conclude that the pathway is complete and determine where VOCs are entering the building. BPC can also be part of the VI investigation toolbox, support the collection of multiple lines of evidence to characterize the VI pathway, and eliminate or limit the collection of subslab vapor samples and/or the number of long-term monitoring events.

BPC data interpretation can be complicated by a variety of factors, including building envelope leakage effects, building or sampling zone complexity, spatial differential pressure distribution during testing, and the presence of indoor sources in areas adjacent to the sampling zone.

After providing a BPC test procedure overview, this TM summarizes the results and presents lessons learned from a series of 10 BPC tests conducted at 9 DoD buildings. These lessons learned are then used to provide recommendations to improve testing procedures and data interpretation.

1 Introduction

1.1 Technical Memorandum Objective

The objective of this technical memorandum (TM) is to provide Remedial Project Managers of the Department of the Navy (Navy) with a rationale for using building pressure cycling (BPC) testing during vapor intrusion (VI) investigations and the preferred procedures for conducting BPC tests. To fulfill this objective, the TM presents an overview of results and lessons learned from a series of BPC tests conducted at several buildings located at Department of Defense (DoD) installations, including large nonresidential buildings (e.g., warehouses) and military housing complexes. Based on the knowledge gained from these tests, this TM provides recommendations to improve testing procedures and data analysis.

1.2 Rationale for Conducting Building Pressure Cycling Testing

BPC consists of using a fan installed through an exterior door or window to induce negative or positive pressure in a building or VI sampling zone within a building. Building or zone depressurization is generally expected to induce subsurface-to-indoor air VI, whereas pressurization tends to suppress VI. The use of BPC to support VI investigations has received increased attention over the past 10 years

(Mosley et al., 2008; MacGregor et al., 2011; McHugh et al., 2012a, 2012b; Beckley et al., 2013; Holton et al., 2015; Tri-Service Environmental Risk Assessment Workgroup, 2017; Lutes et al., 2019; Yao et al., 2019; Guo et al, 2020). The technology is adapted from the energy efficiency industry, which uses BPC techniques to conduct weatherization and building envelope leakage assessments (TEC, 2012; USACE, 2012; Brennan et al., 2014; Retrotec, 2017; ASTM, 2019).

BPC is a technique that can be considered for VI investigations for the following three key applications:

- To assess temporal variability of volatile organic compound (VOC) concentrations indoors
- To identify background sources of VOCs that may not have been readily apparent in a conventional VI building survey
- To locate potential VI entry points

Under certain conditions and building configurations described further herein, BPC testing can be used to conduct a single indoor air sampling event and limit or eliminate the need for follow-up VI sampling or long-term monitoring at a given building (“one round and done”). It can also potentially eliminate the need for more intrusive activities such as the installation of subslab vapor probes (if none are present at the time of testing).

Monitoring of both indoor-to-outdoor and indoor-to-subslab differential pressure (ΔP) is recommended during BPC testing to observe the effects of depressurization/pressurization on the building or sampling zone and evaluate the relative magnitude of the ΔP values. Indoor-to-outdoor ΔP data can readily be obtained using instrumentation mounted on the blower door or a stand-alone ΔP monitor with instrument tubing deployed through a window (or other opening to the outside). Indoor-to-subslab ΔP monitoring requires the installation of at least one subslab probe within the sampling zone to be tested. It is possible, however, to conduct BPC tests with indoor-to-outdoor ΔP monitoring only (i.e., no subslab vapor probes and no indoor-to-subslab ΔP monitoring)[1] and use this information as evidence that depressurization/pressurization is occurring. Monitoring of indoor-to-subslab ΔP only (i.e., without indoor-to-outdoor ΔP monitoring) can also be considered; however, very leaky slabs may show little change in indoor-to-subslab ΔP during BPC testing. This does not mean, under this scenario, that BPC depressurization is not generating conditions conducive to vapor entry, but that indoor-to-subslab ΔP measurements cannot effectively show it is occurring. The leakier the slab, the smaller the magnitude of indoor-to-subslab ΔP relative to indoor-to-outdoor ΔP. Thus, for very leaky slab, indoor-to-outdoor ΔP is more effective for monitoring the BPC test.

VI investigations are often complicated by temporal or seasonal variability of VOC concentrations in indoor air, which can vary by one order of magnitude or more (USEPA, 2012a, p. 11, Figure 1; Holton et al., 2015). To address this variability, regulatory VI guidance documents often recommend that multiple sampling events be conducted during different seasons. Temporal variability is chiefly the result of several factors that occur at the building envelope, including seasonal temperature variations and associated stack effects, wind, barometric pressure changes (i.e., barometric pumping), and the operations of heating, ventilation, and air conditioning (HVAC) systems and other equipment (e.g., exhaust fans). Temporal variability, however, can also occur because of changes at a greater distance from the building along the lengthy pathway of migration of VOCs toward the building, including water table elevation variations (Illangasekare et al., 2014), changes in vadose zone soil moisture (USEPA, 2012b), and continued contaminant migration from historical sources (Carr et al., 2011).

Assuming VOCs attributable to VI are detected in indoor air at concentrations below VI screening levels, investigators may be interested in determining whether VI screening levels could be exceeded in the future by estimating “upper-end” VOC concentrations in indoor air. These concentration estimates can

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[1] This was the case for the BPC tests conducted at Naval Base San Diego (**Section 3.1**), for which there were no subslab vapor probes that could be used for indoor-to-subslab ΔP monitoring.

be obtained with BPC. “Upper-end” indoor air concentrations, which are also called “reasonable maximum exposure” concentrations, are sometimes considered to refer to concentrations equal to or greater than the 90th percentile (USEPA, 2015, Section 10.0; Schuver et al., 2018), meaning that they will occur in no more than 10 percent of sampling events at a given sampling location. It should be noted, however, that the concept of reasonable maximum VI condition (USEPA, 2015) should be properly understood to include not only exposure point concentration, but also the time, frequency, and duration of that exposure (USEPA, 1989; Lutes et al., 2017; Lund, 2020). If upper-end estimates of frequency and duration are used, it may not be necessary to use an upper-end estimate of indoor concentration. Given indoor air concentration variability, it can take multiple sampling events before upper-end concentration conditions are encountered with random, convenience-based (Schuver et al., 2018) or seasonally timed sampling (Holton et al., 2013).

To address both the variability of indoor air concentrations and the relatively low likelihood of sampling indoor air upper-end concentration conditions using convenience- or season-based approaches, BPC artificially generates building pressure conditions that increase the likelihood of migration of VOC vapors from beneath the building into the indoor air, thereby creating “near worst-case” VI conditions under which indoor air can be sampled. The results of indoor air sampling of near worst-case VI conditions induced with BPC enables investigators to estimate reasonable maximum exposure for risk management decisions with no further sampling required (DTSC and WRCB, 2020, p. 23; USEPA, 2015).

The common presence of VOC-containing products and chemicals found inside buildings (USEPA, 2011) often complicates VI investigations. These background sources of VOCs can make it difficult to determine if VI is actually occurring and are generally managed differently with regard to human exposure (e.g., through occupational health systems). The use of BPC can help resolve this issue because background VOCs respond differently to BPC testing conditions than VI-related VOCs do. Thus, BPC can help differentiate VOCs whose presence is unrelated to VI from those that can be attributed to VI.

If the VI pathway is determined to be complete during testing, BPC increases the ability for investigators to determine where subsurface vapors are potentially entering the building (e.g., slab cracks, perimeter cracks, utility penetrations, other preferential pathway) because BPC testing under depressurization conditions enhances vapor transport through these VI entry points. This information is useful to inform mitigation strategies, prioritize mitigation on identified entry points, and limit VI mitigation costs.

1.3 Building Pressure Cycling Testing Overview

1.3.1 Background for Understanding DoD Buildings

DoD commercial/industrial buildings are often large, multipurpose buildings with multiple rooms and several zones served by different HVAC systems. VI in large commercial/industrial buildings must often be evaluated by specific sampling zones depending on a number of factors including air exchange and air flow. HVAC zones are generally defined as portions of the building in which air circulation is controlled by a given thermostat to maintain thermal comfort. These HVAC zones can be readily identified from mechanical diagrams of the building and sometimes field observations. To evaluate VI exposure, sampling zones within the building of interest need to be defined. A sampling zone is an enclosed, occupied location within a building where indoor air sample(s) are collected or could be collected in the future. A sampling zone should have limited air mixing with other building zones. A sampling zone should also be defined such that air is expected to be reasonably well and rapidly mixed throughout the zone. Additional information can be found in various references discussing airflow through buildings and HVAC systems in the context of VI (Tri-Service Environmental Risk Assessment Workgroup, 2009, pp. 144-145; Shea et al., 2010).

Some areas within a given building can be relatively open and highly ventilated, while other areas can be closed and tightly sealed. There can also be areas that are inaccessible or have strict access requirements. Additionally, buildings frequently have subsidiary zones nested within other zones in what is commonly called a "building-within-a-building" configuration. One common example of building-within-a-building configuration is an office space framed out within a larger warehouse. Because of the variety of configurations encountered in commercial/industrial buildings, professional judgment is needed to identify the most suitable sampling zone(s) to conduct a BPC test.

The majority of the VI applications of BPC technology have been to residential or moderate size commercial buildings (less than 20,000 square feet [ft^2] in footprint) (Beckley et al., 2013; Lutes et al., 2019). The U.S. Army Corps of Engineers demonstrated mathematical approaches for sizing blower doors for testing new construction in a building test protocol based on a maximum anticipated acceptable leakage rate at a target pressure (USACE, 2012). They stated that buildings requiring flows greater than 200,000 cubic feet per minute (cfm) at a pressure of 75 Pascals (Pa) "have been successfully tested using standard techniques" for energy efficiency purposes (USACE, 2012, p. 6). Illustrations of the equipment used to conduct tests in large buildings can be found in Genge (2014). This TM focuses on several applications in large commercial or multi-unit residential buildings.

1.3.2 Steps in Performing a Building Pressure Cycling Test

During BPC testing, indoor-to-outdoor (i.e., "cross-building") and indoor-to-subslab (i.e., "cross-slab") ΔP conditions are manipulated to either depressurize or pressurize the building indoor air relative to the outside and subslab (Lutes et al., 2019).[2] Depressurization (negative ΔP) is generally expected to induce subsurface-to-indoor air VI, including near worst-case VI conditions that would be associated with upper-end VOC concentrations in indoor air, whereas building pressurization (positive ΔP) tends to suppress VI. BPC is often—but not necessarily—combined with real-time air sampling using a portable gas chromatography/mass spectrometry (GC/MS) instrument (e.g., HAPSITE) to quantify VOC concentrations in samples collected throughout testing (**Figure 1**). Additional hand-held VOC detectors, such as a photoionization detector (PID) with parts-per-billion-by-volume (ppbv) level detection capabilities (e.g., ppbRAE), may be used to aid in the identification of background indoor sources of VOCs and/or potential entry points for VI (**Figure 2**).

Typical BPC testing can be summarized as follows:

- Baseline data are collected in the building or zone to be tested. These baseline data include VOC concentrations and ΔP data under ambient conditions, including indoor-to-outdoor ΔP and indoor-to-subslab ΔP. Tracer testing can also be used to estimate the building or zone air changes per hour (ACH) under ambient conditions. The ACH, also called air exchange rate, is the number of zone interior air volumes exchanged per hour. ACH values can vary depending on building type and conditions—with "leaky" buildings associated with greater ACH—but typically range from 0.1 to 4 air volumes exchanges per hour.[3] For some buildings, information allowing calculation of baseline ACH (i.e., ACH under ambient conditions) can be obtained from recent testing and balancing studies, which are frequently performed as part of building commissioning, retro-commissioning, or energy audits.
- A blower door equipped with a fan (e.g., Minneapolis blower door system) moves air from inside to outside of the building room or zone to be tested (depressurization, which tends to induce VI) or from outside to inside (pressurization, which tends to suppress VI). In some cases, an alternate

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[2] In this TM, indoor-to-outdoor ΔP is defined as the difference between the indoor pressure and the outdoor pressure. A positive ΔP indicates that the indoor pressure is greater than the outdoor pressure (i.e., the building is pressurized relative to the outside), whereas a negative ΔP indicates that the indoor pressure is smaller than the outdoor pressure (i.e., the building is depressurized relative to the outside).

[3] In residential settings, the ACH for whole structures has been found to range from 0.1 to 1.5, with a median of about 0.45 (USEPA, 2017, p. 51, Table 9). For commercial buildings, a mean ACH of 1.5 and a range of 0.3 to 4.1 have been reported (USEPA, 2018, p. 19-18, Table 19-30). Elevated ACHs reflect more leaky buildings and/or HVAC system operation in certain specialized facilities. For example, ventilation standards (ASHRAE, 2019) require exhaust rates of 1.5 cfm/ft^2 or greater in certain specialized rooms, such as auto repair rooms, most animal facilities, and chemical storage rooms, which would correspond to an ACH of 6 or greater, assuming a building height of 15 feet.

blower already part of the building can be used (e.g., “whole-building exhaust fan”, high-volume ventilation systems associated with a paint spray booth).

- The test is conducted in incremental steps, typically two to three depressurization steps and one pressurization step. The pressure cycling duration of each step depends on the volume of the sampling zone and the flow rate needed to achieve a target indoor-to-outdoor ΔP across the blower door. After ΔP control has been adequately established through adjustment of the blower door operating conditions, a minimum of three air exchanges is typically needed to establish stable VOC concentration conditions within the zone.
- Indoor-to-outdoor and indoor-to-subslab ΔPs are monitored before and during testing to assess the relationship between VOC concentrations, ACH, and ΔP. Monitoring both indoor-to-outdoor and indoor-to-subslab ΔPs is preferred during testing to better understand the relative importance of vapor entry (driven by indoor-to-subslab ΔPs) and air exchange (driven by indoor-to-outdoor ΔPs). In certain buildings, however, subslab vapor probes may not have been installed, so indoor-to-subslab ΔP monitoring is not possible. Even if indoor-to-subslab ΔP monitoring is not conducted, it can be expected that BPC depressurization will generate conditions conducive to vapor entry from the subslab into indoor air.
- If the blower door controls indoor-to-outdoor ΔP for the tested zone, then measurements of the flow rate through the blower door can be used to compute the sampling zone ACH (using the room volume). This is based on an assumption that in a negative ΔP test (depressurization), the flow measurable at the blower door is the dominant route by which air exits the zone. Similarly, in a positive ΔP test (pressurization), the assumption is made that the air measured going across the blower door is the dominant source of air flow into the zone.

1.3.3 Interpreting Building Pressure Cycling Test Results

Mathematical Relationships

The concentration of a VOC in indoor air that is impacted solely by VI in a single-zone building is determined by the balance between the volumetric rate of entry of soil gas (Q_{soil}) and the building ventilation rate ($Q_{building}$). The building ACH is proportional to $Q_{building}$. During the depressurization portion of a BPC test, both Q_{soil} and $Q_{building}$ increase, with the ratio of their increase governed by the resistance to flow provided by the following:

- The floor and underlying materials (e.g., slab, gravel, moisture barrier, soil)
- The walls or roof of the building (e.g., open windows, vents, cracks)

If Q_{soil} increases to a greater degree than $Q_{building}$ during depressurization, and the VOC concentration in subslab vapor remains constant, then the VOC concentration in indoor air will increase. If, however, turning on the blower door pulls air more easily from the outside (through leakage) than from the subslab, Q_{soil} increases to a lesser degree than $Q_{building}$, and the observed VOC concentration in indoor air will decrease even if the mass flux of VOCs into the building increases as a result of depressurization.

During the pressurization portion of a positive BPC, the resulting $Q_{building}$ is expected to be similar to the $Q_{building}$ achieved during depressurization with a similar absolute value of indoor-to-outdoor ΔP. Thus, the dilution effect on indoor air concentrations, if any dilution is observed, is expected to be equivalent.

If, during depressurization, air is drawn in from an adjacent zone in a multizone building, the interpretation becomes more complex. For example, there could be VI occurring into the adjacent zone, or an indoor source of VOCs in the adjacent zone.

Direct Interpretation of Observed Concentrations

BPC tests can be interpreted in terms of the concentration of the target VOC in indoor air or in terms of changes to the mass flux of VOCs entering the building from VI. The mass flux-based interpretation approaches are discussed in the next subsection. The typical initial interpretation of BPC based on concentration observations is as follows:

- If a VOC concentration in indoor air increases with increasing depressurization (negative ΔP) and the indoor air concentration decreases with positive pressurization, then VI is a likely source of the VOC in indoor air.
- If a VOC concentration remains generally unchanged or decreases during pressure cycling, background sources of the VOC may be present.

Interpretation can be complicated if there is substantial leakage across the building or sampling zone envelope (e.g., windows, doors, vents, structure interstices). There is always some degree of leakage during BPC in response to depressurization or pressurization because the structure is rigid, and the air moving through the blower door needs to enter or exit the structure somewhere else (e.g., through the slab, roof, windows, or building envelope). However, study buildings or zones with a leaky envelope will achieve a set target ΔP with a greater blower door flow rate than buildings or zones with a “tight” envelope, such that the ACH will be greatest for leaky buildings or zones. Thus, for buildings with a leaky envelope, the VOC concentrations in indoor air obtained during depressurization testing may be partially diluted by outdoor air leakage and the indoor air concentrations measured under depressurization conditions may underestimate concentrations that would be representative of near worst-case VI conditions.

Figure 1. HAPSITE and blower door.

Figure 2. Vapor Intrusion entry point and a PID.

Interpretation Based on Mass Discharge Principles (Mass Flux-Based Interpretation)

For a given sampling zone of volume (V_{SZ}) with a given baseline VOC concentration in indoor air (C_{IA}), the VOC mass present (M_{IA}) in the indoor air is:

$$M_{IA} = V_{SZ} \text{ x } C_{IA} \qquad [1]$$

Given a baseline ACH (ACH_{BL}) (i.e., ACH under ambient conditions), the amount of air leaving the sampling zone every hour corresponds to the zone ventilation rate Q_{zone}:

$$Q_{zone} = V_{SZ} \text{ x } ACH_{BL} \qquad [2]$$

Similarly, the VOC mass leaving the sampling zone every hour ($Disch_{zone}$) under baseline conditions is:

$$Disch_{zone} = C_{IA} \text{ x } Q_{zone} = C_{IA} \text{ x } V_{SZ} \text{ x } ACH_{BL} \qquad [3]$$

Assuming the VOC concentration in indoor air remains constant, the VOC mass leaving the sampling zone is replaced by VOC mass influx from the subsurface related to VI (an equilibrium condition).

During BPC, the study space is depressurized to potentially increase the VOC mass influx from the subsurface; however, leakage of “clean” air through the building envelope (e.g., walls, roof, openings, such as door) can mask the additional VI-related VOC mass influx and decrease the VOC concentration in indoor air. The VOC mass discharge at the blower door ($Disch_{BD}$) during BPC testing is obtained by multiplying the VOC concentration at the blower door (C_{BD}) by the blower door fan flow rate (Q_{BD}):

$$Disch_{BD} = C_{BD} \text{ x } Q_{BD} \qquad [4]$$

An increase in VOC mass discharge with increasing depressurization is generally indicative that VI may be occurring within the sampling zone because most indoor sources are presumed to have constant mass discharge. A corrected indoor air concentration under testing conditions to account for dilution effects can be obtained by multiplying the amount of VOC mass influx from the subsurface, which is equal to the mass discharge at the blower door ($Disch_{BD}$), divided by the amount of air replaced under baseline (ambient) conditions (Q_{zone}) (the zone ventilation rate):

$$C_{IA} = \frac{Disch_{BD}}{Q_{zone}} = \frac{C_{BD} \times Q_{BD}}{V_{SZ} \times ACH_{BL}} \qquad [5]$$

Therefore, the ratio C_{BD} x Q_{BD} x 60 / (V_{SZ} x ACH_{BL}) in units of micrograms per cubic meter (µg/m^3) can provide an estimate of upper-end indoor air concentration under near worst-case VI conditions.[4] This concentration represents the VOC concentration that could be present in indoor air if the VOC mass influx from the subsurface obtained during BPC testing was achieved under ambient conditions with no BPC-induced leakage.

As an illustration, consider a VI sampling zone with a footprint of 6,000 ft^2 and a height of 10 feet, with an ACH of 1.5 and an indoor air concentration for a given VOC equal to 2 µg/m^3 under baseline conditions. The zone ventilation rate under baseline conditions is therefore (using Equation [2]):

$$\frac{6{,}000 \text{ ft}^2 \times 10 \text{ feet} \times 1.5 \text{ [per hour]}}{60 \text{ [minute per hour]}} = 1{,}500 \text{ cfm}$$

The VOC mass leaving the sampling zone every minute under baseline conditions is (based on Equation [3]):

$$1{,}500 \text{ cfm} \times (0.3048 \text{ [meter per foot]})^3 \times 2 \text{ µg/m}^3 \approx 85 \text{ micrograms per minute (µg/min)}$$

which is also the VOC mass influx from the subsurface related to VI under equilibrium conditions. Now, consider the same sampling zone during BPC testing and assume that the blower door flow rate to

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[4] The ratio presented herein assumes that blower door fan flow rate Q_{BD} is expressed in units of cfm and the zone volume V_{SZ} in cubic feet (ft^3). The factor of 60 converts the ACH to air changes per minute.

achieve the target depressurization step is 12,000 cfm, with a measured VOC concentration of 0.5 µg/m^3 at the blower door. The ACH under testing condition is therefore (using Equation [2]):

$$\frac{12{,}000\ \mathrm{cfm}\ \times\ 60\ [\text{minute per hour}]}{6{,}000\ \mathrm{ft}^2\ \times\ 10\ \text{feet}} = 12$$

The VOC mass discharged by the blower door can be calculated as (using Equation [4]):

$$12{,}000\ \text{cfm} \times (0.3048\ [\text{meter per foot}])^3 \times 0.5\ \mu\text{g/m}^3 \approx 170\ \mu\text{g/min}$$

which is double the VOC mass influx under equilibrium conditions (85 µg/min), even though the observed concentration at the blower door (C_{BD}) is only a quarter of the concentration under equilibrium conditions.

Assuming that the discharge of 170 µg/min corresponds to a VOC mass influx from the subsurface under near worst-case VI conditions, the resulting indoor air concentration can be estimated as (using Equation [5]):

$$\frac{170\ \mu\mathrm{g/min}}{1{,}500\ \mathrm{cfm}\ \times\ (0.3048\ [\text{meter per foot}])^3} = 4\ \mu\mathrm{g/m}^3$$

which corresponds to the indoor air concentration associated with an increased VOC mass influx from the subsurface (170 µg/min) assuming the ACH of 1.5 under baseline conditions.

This method of calculating a worst-case indoor air concentration is expected to be overly conservative because most conditions that increase the flow across the slab (Q_{soil}) also increase the air exchange (ACH) and zone ventilation rate (Q_{zone}). It is likely, however, that the pressure distribution in the building induced by the BPC test differs somewhat from the pressure field induced under natural conditions by winter “stack effects” (USEPA, 2015, p. 28). The BPC depressurization portion of the test acts by reducing the pressure in the entire zone. Thus, it changes the pressure differential between outside and inside (Q_{zone} and thus ACH) to the same degree that it changes the pressure differential between subslab and indoors (Q_{soil} and thus VI mass discharge). In a “stack effect” situation in a slab-on-grade structure, the stack effect depressurizes the bottom portion of the zone and positively pressurizes the top portion of the zone.

In other words, depressurization with a blower door provides a roughly equal force for air to seep in through the slab from the subslab, a few feet off the floor from a leaky window, or near the top of the structure from the attic vent. By contrast, a natural stack effect depressurizes the slab surface relative to the subslab, depressurizes the bottom portion of the exterior wall relative to the outside, results in neutral pressure a few feet above floor level, and pressurizes the attic.

Summary Regarding Test Interpretation

In summary:

- An interpretation made by using the highest VOC concentration in indoor air observed during a BPC test for comparison with a screening or action level will frequently underestimate the indoor air concentration under near worst-case VI conditions.
- An interpretation made by assuming the highest mass discharge observed in a BPC test will occur with a “typical” or average ACH will frequently overestimate the indoor air concentration under near worst-case VI conditions.

These bounding concentration estimates, however, may be sufficiently accurate for practical decision-making. If a more refined answer is required, additional information from tracer tests of ACH and long-term observations of ΔP across the slab and walls could support a more refined definition of the reasonable worst-case performance of a given building.

2 Overview of Building Pressure Cycling Test Dataset

This TM focuses on a selection of 10 BPC tests conducted at 9 buildings at 4 DoD installations. A BPC test overview along with key test metrics and data are presented in this section. The next section (**Section 3**) provides individual test reporting and lessons learned from the various BPC tests.

As noted previously, the general approach for BPC testing is to obtain baseline VOC and ΔP data then depressurize at two or three indoor-to-outdoor ΔP targets (e.g., -5, -10, and -15 Pa) and one positive indoor-to-outdoor ΔP target (e.g., +5 Pa). At each target ΔP, VOC concentrations are allowed to reach equilibrium, which generally is observed to occur after three air exchanges. While this represents a typical approach, the designs of studies presented herein were modified as necessary based on several factors such as building size, leakage rate, time constraints, and specific building considerations (e.g., door location, building usage, security level). The series of BPC tests discussed in this document can be summarized as follows:

- The dataset includes 10 BPC tests conducted in 9 buildings, consisting of base housing, warehouses, office spaces, training facilities, and maintenance shops.
- BPC testing was performed at these buildings based on two different rationales: seven of the buildings were selected based on their proximity to chlorinated VOC groundwater plumes combined with limited “traditional” VI data (i.e., indoor air, subslab vapor, or soil vapor); the other three buildings were selected for BPC testing based on indoor air data from prior investigations with results that exceeded indoor air screening levels (IASLs) or other target levels.
- The tests were conducted between February 2015 (winter) and August 2019 (summer).
- The sampling zone volumes spanned two orders of magnitude ranging from 1,841 to 145,800 ft^3.
- The blower door flow rates ranged from 100 to 3,086 cfm, resulting in ACH ranging from 0.37 to 33 air exchanges per hour.
- Under depressurization conditions, target indoor-to-outdoor ΔP ranged from -1 to -25 Pa.
- Under pressurization conditions, target indoor-to-outdoor ΔP ranged from +5 to +15 Pa.
- The duration of each step target ranged from 12 to 345 minutes (typically around 1 to 2 hours per step).

Individual BPC test procedures and results are summarized in **Section 3**. The following information is presented for each building of interest: (1) a summary of the test outcome at each building, and (2) lessons learned from the BPC test data. Tables detailing building usage and its relationship to VI and tables summarizing the BPC test data are included in **Attachment A**. Unless otherwise indicated, “sampling” refers to indoor air sampling conducted using a HAPSITE. Additionally, the following terms are used during the discussion:

- “Initial investigation under ambient conditions” refers to indoor air sampling conducted at least a day prior to conducting BPC testing to determine whether VOC concentrations are exceeding IASLs under typical operating ΔP conditions of the building (i.e., no BPC taking place).
- “BPC baseline testing” refers to indoor air sampling conducted immediately prior to the BPC depressurization/pressurization steps; BPC baseline testing is therefore also under ambient ΔP conditions.
- “Negative ΔP step” follows BPC baseline testing and refers to the depressurization portion of the BPC test intended to induce VI (typically two to three steps).
- “Positive ΔP step” follows the depressurization steps and refers to the pressurization portion of the BPC test intended to suppress VI (typically one step).

- Unless otherwise indicated, ΔP refers to the indoor-to-outdoor ΔP as opposed to indoor-to-subslab ΔP. While measuring both indoor-to-outdoor ΔP and indoor-to-subslab ΔP is the preferred approach (as was noted previously), indoor-to-subslab ΔP was not consistently measured during testing because subslab vapor probes were not always available in the tested buildings.

3 Building Pressure Cycling Testing Results and Lessons Learned

This section provides summary information and lessons learned from a series of 10 tests conducted at 9 buildings at 4 installations, including the following:

- Two installations located in southern California (six tests conducted in six buildings of Installation A and one test conducted in a building of Installation B)
- An installation located in Virginia (two tests in two different zones of a building)
- An installation located in North Carolina (one test in a building)

As noted previously, additional building information and BPC test summary data are provided in **Attachment A**.

3.1 California Installation A – Various Buildings

3.1.1 Warehouse-Type Building

Summary of the Test Outcome

The BPC test took place in an office space within a large warehouse building (**Figure 3**). Trichloroethene (TCE) was detected at concentrations below the IASL during initial investigation under ambient conditions and during the BPC baseline sampling. The TCE concentrations decreased below instrument detection limits during the negative ΔP steps, then increased during the positive ΔP step to approximately the same concentration measured during baseline sampling. Absent detections of TCE in the outdoor air being supplied to the test zone during the positive ΔP step, this data pattern suggested that there was a background indoor source of TCE within the room. This conclusion was confirmed by discovery of an acrylic cement containing TCE (IPS Weld-On 4 acrylic) in a solvent storage cabinet near the blower door (**Figure 3**).

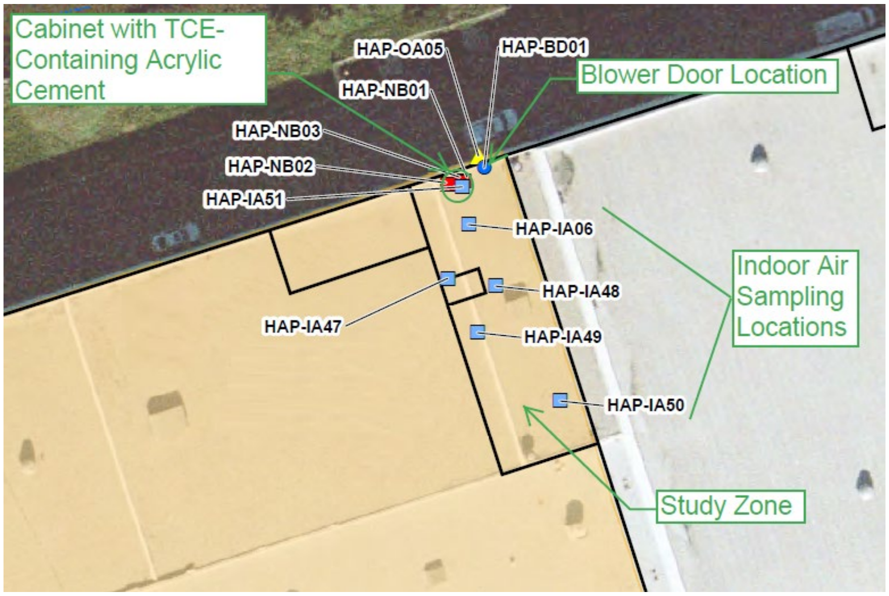

Figure 3. Warehouse BPC test configuration.

Lessons Learned

In this BPC test, the absence of TCE in indoor air during the depressurization portion of the test and its presence during pressurization were strong indicators that TCE was unlikely to be the result of VI. Assuming TCE had been the result of VI, the absence of TCE detections in indoor air during depressurization could have been possible with a relatively low-strength subsurface VI source associated with baseline indoor air concentrations slightly above instrument detection limits. The combination of low indoor air concentrations with substantial leakage during depressurization (i.e., high ACH) could have resulted in nondetects. In this test, however, the baseline TCE concentrations were up to six times greater than the instrument detection limit and the ACHs ranged from 1.6 to 2.3, which are not indicative of substantially elevated leakage across the building envelope.

Of particular interest to this test was also the location of the storage cabinet proximate to the blower door (**Figure 3**). This configuration resulted in nondetects during depressurization, as well as positive detections during pressurization by contributing TCE to the air pushed into the room by the blower door fan. Different indoor source locations relative to the blower door would likely result in different patterns.

Additionally, the positive pressure portion of the BPC test showed that the indoor air concentrations associated with the indoor source were comparable to the concentrations measured during baseline testing. This suggests that the Q_{zone} at +5 Pa was not far from the unmeasured baseline (ambient) Q_{zone}, such that the ACH of 1.6 at +5 Pa was in the ballpark of the unmeasured baseline (ambient) ACH.[5]

3.1.2 Residential Building 1

Summary of the Test Outcome

During initial investigation conducted under ambient conditions, tetrachloroethene (PCE) was detected above the IASL in several residential suites (typically consisting of sets of two rooms with a shared space). One of the suites was selected for BPC testing because it was assumed to represent worst-case conditions based on its location in the building and the results of the initial investigation. BPC baseline indoor air sampling indicated PCE concentrations were below the IASL. The PCE concentrations increased above the IASL during the negative ΔP steps, then decreased below instrument detection limits during the positive ΔP step. The mass discharge through the blower door also increased by about 50 percent between the two depressurization steps. Overall, this dataset indicated that subslab vapor was the primary source of the PCE and that the VI pathway was complete, with concentrations exceeding the IASL. During further testing, VI entry points consisting of multiple utility penetrations through the building slab were identified in wall cavities. The PCE concentrations increased significantly at those entry points between baseline conditions and negative ΔPs, an indication that these entry points were likely contributing PCE to indoor air.

Lessons Learned

This BPC test is a good illustration of the expected test response when VI is occurring; specifically, the increase in PCE concentrations relative to baseline concentrations during the depressurization steps and their reduction to levels below instrument detection limits during pressurization. In addition, the ACHs were low enough for the PCE concentrations to increase with each depressurization step. Had leakage been significant, the concentrations may have not increased, but computation of the PCE mass discharge through the blower door (by multiplying PCE concentration at the blower door by the blower door fan flow rate; see Equation [4]) would have ultimately been used to show that the PCE discharge was increasing with each negative ΔP step, thereby providing evidence that VI was occurring in the sampling zone. Conducting the BPC test also made it possible to identify locations where PCE was

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[5] This was further supported by the longer-term ambient monitoring ΔPs, which were measured to range from about -2.5 to +15 Pa (with a positive average of +1.6 Pa) during a 2-week period prior to and after the BPC test was conducted.

entering the room (i.e., wall cavities), a determination that later facilitated building mitigation. Conventional VI investigations conducted under ambient conditions would most likely not have readily identified these VI entry points.

Another observation related to this test was that the blower door flow rate required to reach the +15 Pa pressurization step was about twice the flow rate needed to reach the “mirror” depressurization step with the same absolute value (-15 Pa). Such conditions are indicative of strongly negative ΔPs under ambient conditions (i.e., pre-test conditions). These strongly negative ambient ΔPs would cause VI in the presence of a subsurface VOC source. More neutral ΔPs under ambient conditions would result in equivalent blower flow rates for the mirror pressurization and depressurization steps (±15 Pa).

3.1.3 Residential Building 2

Summary of the Test Outcome

During initial investigation conducted under ambient conditions, PCE was detected above the IASL in one of the residential suites (consisting of a set of four apartments with a shared space). The apartment with the highest PCE concentration among those tested in the initial round was selected for BPC testing (**Figure 4**). Although nondetect during BPC baseline indoor air sampling, PCE was detected during testing and the PCE concentrations increased above the IASL during the negative ΔP steps, before decreasing back to below instrument detection limits during the positive ΔP step. The mass discharge through the blower door increased by close to 50 percent between the two depressurization steps. No internal mixing fan was used within the tested zone. While this pattern was indicative of a complete VI pathway, with concentrations exceeding the IASL, samples collected inside a closet containing a dry-cleaned uniform in a garment bag were also suggestive of a background indoor source (closet A; **Figure 4**). The PCE concentrations in this closet were found to continuously decrease during the negative and positive ΔP steps; however, these concentrations remained relatively stable when adjusted for dilution (e.g., by multiplying the PCE concentration in the closet by the ratio of flows required to achieve the -15 and -10 Pa pressure targets). This pattern was further confirmation that the uniform was a background source of PCE to indoor air. Testing inside the garment bag indicated that PCE was present at concentrations almost three orders of magnitude greater than PCE concentrations measured in the apartment. The BPC testing was repeated 3 weeks later, after removing the uniform, and PCE was not detected during baseline or any of the pressure steps, confirming that the uniform and garment bag was the background source of PCE in the apartment and that there was no PCE-related VI occurring in the suite.

Lessons Learned

This example shows the potentially confounding nature of certain BPC tests and the need to use caution when interpreting test data and to adjust the BPC approach as warranted by findings. Initial indications from this test were that PCE was present because of VI; however, further investigation revealed a background indoor source in the closet. Essentially, VOC-containing vapors were “intruding” into the indoor air not from the subsurface but from the closet.

Positioning of the sample locations and blower door was also important. The configuration of this BPC test was such that the room indoor air sampling location during testing (HAP-IA21; **Figure 4**) was between the blower door and the closet containing the background source.[6] During depressurization (negative ΔP), the air from within the closet was drawn past the sampling location and through the blower door which resulted in increased PCE concentrations in indoor air.

During pressurization (positive ΔP), air was blown from the outside, past the room indoor air sampling location, and toward the closet and surrounding walls.
PCE diffusing from inside the closet to the apartment may

BPC test configuration (blue and red arrows

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[6] The other indoor air sampling location was located in the bathroom (HAP-IA35; **Figure 4**); PCE was only detected once at that location during the initial depressurization step and its concentration remained below instrument detection limit during the subsequent steps.

have been diluted by the incoming outside air to concentrations below the instrument detection limit. In addition, because the closet has a backwall with an unpressurized adjacent space, it is possible that some of the air passing over the indoor source could have been discharged from the room via the closet without an opportunity to mix. If an indoor air sampling location downstream from the closet had been selected, that location may have resulted in elevated PCE concentrations. In this instance, adding a location inside the closet during the BPC test helped identify the background indoor source.

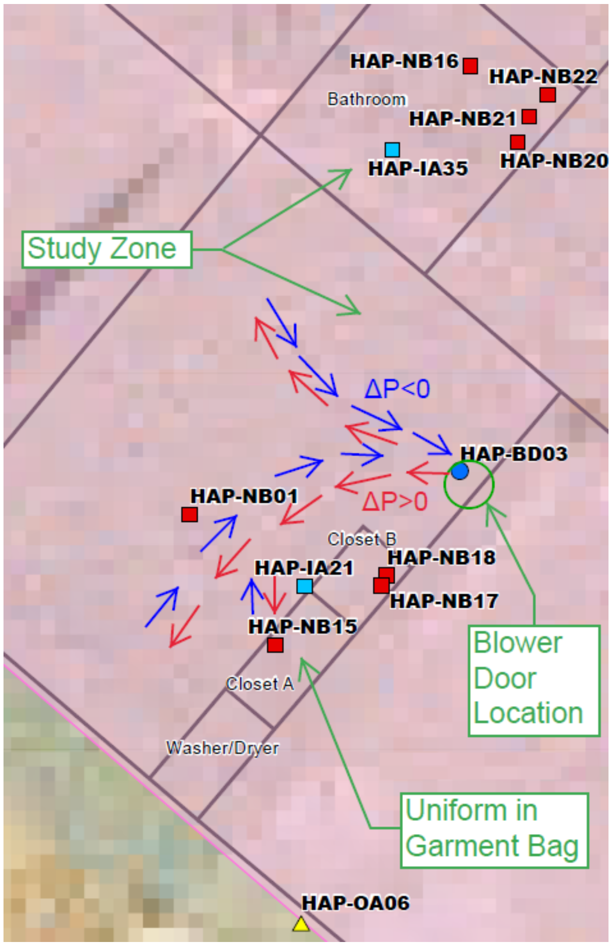

Figure 4. Residential Building 2 BPC test configuration.
Blue and red arrows indicate air flow movement during depressurization.

3.1.4 Instruction Facility 1

Summary of the Test Outcome

The BPC test took place in one of the building wings, consisting of a lobby, corridors, and multiple rooms, totaling close to 130,000 ft^3 (one of the largest test volumes in this dataset). During the initial investigation under ambient conditions, PCE was detected below the IASL. On the day of BPC testing, however, the PCE concentrations during baseline sampling were above the IASL. The PCE concentrations increased during the negative ΔP steps, then decreased during the positive ΔP step (which took place the following day). During depressurization, PCE increased throughout the building, but increased most significantly in one room where the highest PCE concentrations in indoor air were detected. The mass discharge through the blower door also increased by more than 70 percent between the two negative steps. Overall, this dataset indicated that the VI pathway was complete, with concentrations exceeding the IASL. During further investigation conducted at a later time, VI entry points consisting of multiple utility penetrations through the building slab were identified in the floor. A large perimeter crack was also found in the floor along the wall interface of the room with the highest PCE concentrations.

Lessons Learned

The difficulty associated with this BPC test was primarily due to the size of the sampling zone, which created several challenges including the following:

- Incomplete mixing of zone – The wing was designated as a single HVAC zone for VI investigation purposes because it is served by a common air handler, albeit with eight variable air volume terminal units. The BPC testing, however, was conducted on the weekend when the HVAC system was not on, which most likely resulted in limited air mixing through the zone.
- Test duration – It was not possible to run the entire BPC in a single day. For instance, the -5 Pa step was achieved at a blower door flow rate that resulted in an ACH of close to 0.5, meaning about 6 hours were needed to achieve three sampling zone air exchanges.
- Representativeness of ΔP data – Two ΔP monitors (Omniguard instruments) were deployed within the building to record ΔP in addition to the readings recorded at the blower door. The readings indicated that ΔPs were not consistent across the building. For instance, for the -5 Pa depressurization step, the two Omniguard instruments read -2.5 and -7.7 Pa on average. The difference can be explained by the fact that different building sides may experience different outdoor pressures as a result of wind effects. Alternatively, this result could suggest the partial "segmentation" of the tested interior zone (i.e., different interior pressures in different subsidiary zones within the sampling zone). This example also illustrates that response to depressurization may not necessarily generate air movement in certain building areas that are away from the blower door, particularly when the sampling zone is large and incompletely mixed under ambient conditions. It is possible that the bulk of the air flow comes from a few preferential locations within the building with potentially little effect, if any, on building areas where VI is occurring. Positioning the blower door at a location where VI is suspected may help generate a more favorable test outcome; however, options for positioning the blower door in a given sampling zone are often limited. In some residential studies, box fans are used to enhance mixing within the tested zone; however, that is logistically difficult in a space with a volume of 130,000 ft^3.
- Representativeness of PCE concentrations – As noted previously, PCE concentrations generally increased during depressurization and decreased during the pressurization cycle that was conducted the following day. Notably, however, the PCE concentrations were measured to be highest during baseline sampling conducted on the morning of the pressurization cycle. This was interpreted as the PCE concentrations continuing to increase overnight after the depressurization cycle was completed. Thus, near worst-case conditions were not necessarily achieved during depressurization (even though the test was successful at confirming the occurrence of VI and identifying the location of VI entry points). A possible explanation for these observations is that subsurface vapors were mobilized during depressurization testing (potentially pulled toward the building) and continued to enter the sampling zone overnight at a time the HVAC system was off and ΔPs likely remained negative. Another possible explanation is that the primary point of entry under depressurization conditions was at some distance away from the monitoring locations with insufficient air mixing occurring during the test. This is an indication that three air exchanges may not be sufficient to achieve near worst-case conditions in partially subdivided zones of large volumes (though BPC testing may indicate whether VI is occurring and where). This example suggests that a single BPC test may have some limitations in instances where sampling zones are greater than 100,000 ft^3 and that additional lines of evidence, such as BPC tests where multiple rooms are successively depressurized, may be needed to comprehensively characterize the VI pathway for buildings of that size. Use of mixing fans may also be considered to help decrease uncertainties in data interpretation.

3.1.5 Instruction Facility 2

Summary of the Test Outcome

BPC testing was conducted in a mailroom of the building. PCE was detected above the IASL during both the initial investigation under ambient conditions and the BPC baseline sampling. During the negative ΔP steps, the PCE concentrations in indoor air decreased below the instrument detection limit; the PCE concentrations remained below detection during the positive ΔP step. This pattern was potentially indicative of a background indoor source of PCE within the room; however, no background sources of PCE could be identified. To further assess PCE sourcing, a flux chamber was placed on the mailroom floor, and sampling from the chamber showed an increase in PCE concentrations over time, indicating that a source of PCE was present in or beneath the floor. Subslab vapor sampling was subsequently performed. PCE concentrations in subslab vapor did not exceed 40 $\mu g/m^3$, which were too low to result in the observed indoor air concentrations through VI from the subslab (even when using the most conservative subslab vapor-to-indoor air attenuation factors, such as the United States Environmental Protection Agency generic attenuation factor of 0.03, which is based on residential structures [USEPA, 2015]). Absent other preferential pathways in the mailroom, it was concluded that there must be a source related to the flooring material (e.g., tile adhesive) or in the concrete slab (e.g., from a release of PCE-containing chemical, or adsorption of PCE into the concrete over time) and not conventional VI. Recent studies have suggested that concrete slabs can adsorb a substantial amount of VOC mass (Musielak et al., 2014).

Lessons Learned

This example illustrates potential challenges associated with certain BPC tests; caution should be used when interpreting test data and additional lines of evidence collected where appropriate. Initial indications from this test were that a PCE background source was present; however, none could be readily identified. Flux chamber results suggested that diffusive PCE transport may be occurring from the slab. Elevated ACH required to achieve pressure targets diluted PCE concentrations to below instrument detection limits, further complicating data interpretation. BPC data were not sufficient to assess VI potential because BPC tests are not designed to differentiate desorption (from flooring materials) from subslab VI. Ultimately, additional activities were needed to complete this VI assessment, including the installation of subslab vapor probes.

3.1.6 Instruction Facility 3

Summary of the Test Outcome

During the initial investigation under ambient conditions, chloroform was detected above the IASL at generally similar concentrations throughout the building. Several background indoor sources of chloroform were also identified in the building, as is common for chloroform and other trihalomethanes (e.g., by-products in drinking water that undergoes chlorination or by-products of bleach-containing detergents) (Olson and Corsi, 2004; NJDEP, 2016). BPC testing was conducted in one of the classrooms because chloroform was detected in a floor drain at a concentration that was one order of magnitude greater than indoor air. During the negative ΔP steps, the chloroform concentrations in indoor air remained about the same as those measured during baseline sampling. During the positive ΔP step, the chloroform concentrations decreased to concentrations similar to those measured outdoors. The chloroform concentrations in the drain also decreased during the negative ΔP steps. This suggested that the drain was not a potential preferential pathway for VI, but rather a weak background indoor source related to municipal water and/or cleaning products poured down the drain. The test data were also indicative of multiple weak background indoor sources of chloroform, which were either present in the classroom at the time of testing or migrated into the room through leakage from other building locations during the negative ΔP steps.[7]

Lessons Learned

This example illustrates the difficulty of assessing certain background VOC sources, such as chloroform, that may be present in indoor air as a result of water chlorination or from cleaning products. The presence of chloroform in drains and sewer utility lines may be mistakenly assumed to be the result of VI through utility preferential pathway, where in fact it can be attributed to chlorination of water. BPC testing, combined with an understanding of VOC concentration distribution in the surrounding building air, can help support data interpretation and differentiate VI from background sources associated with the sewer utilities. A potentially complicating factor is that, during a BPC test, it can be difficult to discern a weak indoor VOC source (i.e., finite in mass and transport ability, such as chloroform in a drain) from VI-related VOCs that are being diluted as a result of leakage (e.g., increased ACH). Thus, both BPC testing experience and experience relative to typical background sources and the VOCs associated with these sources are important to assess test data.

3.2 Warehouse-Type Building at Virginia Installation

The building is a large warehouse-type building, in which several office spaces and other rooms are located. Several BPC tests were conducted at various building locations. This section focuses on two tests conducted within the building.

3.2.1 Office

Summary of the Test Outcome

The BPC test took place in an office, where TCE was detected at a concentration of 25 µg/m^3 during an initial VI investigation (indoor air sampling using an evacuated canister). Subsequently, during BPC baseline sampling, TCE was detected at a lower concentration up to 17 µg/m^3. The TCE concentrations remained at approximately the same levels during the three negative ΔP steps (up to 14 µg/m^3).[8] The flow rates required to meet the negative ΔP targets resulted in ACHs ranging from 19 to 32—or at least one order of magnitude greater than the baseline ACH of 0.74 measured by tracer testing under ambient conditions—an indication that this office was a leaky zone in which depressurization was difficult to achieve. Leakage through the room envelope generated conditions conducive to diluting the TCE concentrations within the office, indicating that near worst-case VI conditions may not be directly determined from the peak concentration observed during the BPC test (14 µg/m^3). The initial evacuated canister sampling result of 25 µg/m^3 directly showed that under certain conditions, baseline concentrations could be greater than those obtained during BPC testing.

To account for potential dilution effects, TCE mass discharges were calculated based on the TCE concentrations detected at the blower door and the fan air flow rates. The mass discharges were observed to increase during each negative ΔP step, with a 70 percent increase between the -5 and -15 Pa steps. If these worst-case mass discharges were used along with the baseline ACH to estimate a worst-case indoor air concentration, the predicted value would range from 190 to 320 µg/m^3 (based on the -5 to -15 Pa pressure steps) using the mass flux approach discussed in **Section 1.3.3**. For comparison, a concentration of 25 µg/m^3 was measured in the only baseline 24-hour sample collected prior to mitigation.

Overall, this dataset supported the conclusion that the VI pathway was complete. It also illustrated, as discussed in **Section 1.3.3,** how the highest VOC concentration observed during BPC testing could be

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[7] These indoor sources can also be intermittent (e.g., chloroform emissions from shower, washing, or dishwasher operation).

[8] A positive ΔP step was not performed because of time constraints for conducting the test in the office and because there was sufficient evidence to conclude that the VI pathway was complete.

lower than the upper-end indoor air concentration. The dataset also showed how mass discharge calculations could help in estimating an upper-end indoor air concentration.

Further sampling conducted during the BPC test using both the HAPSITE and a PID revealed the presence of VI entry points consisting of a large gap running along the base of the wall. The PID readings taken from the gap almost doubled from 11 to 20 parts per million by volume between baseline conditions and the -15 Pa step, an indication that the subslab was likely contributing TCE to indoor air through the gap.

Lessons Learned

This example illustrates how, under certain conditions, near worst-case concentrations may not be directly observed during BPC testing. In this example, leakage through the room envelope resulting in large ACHs during depressurization relative to the baseline ACH, most likely created substantial dilution effects.

During the negative ΔP steps, negative indoor-to-subslab ΔPs were observed, but were generally only about one-half of the indoor-to-outdoor ΔPs. This suggests that the floor system provides less resistance to flow than the walls/ceilings, which is consistent with the observed large floor-wall gap. Since advection-driven VI results from negative indoor-to-subslab ΔPs, it is possible that near worst-case VI conditions are achieved in instances where indoor-to-subslab ΔPs are negative, but at a magnitude comparable to or more negative than indoor-to-outdoor ΔPs. This condition cannot readily be achieved during BPC testing, likely because of the very leaky floor-wall gap. As discussed in **Section 1.3.3**, there are natural conditions under which the ΔP fields are more “focused” at the floor level, while BPC testing can drive large flows across the walls or ceiling of the zone.

This dataset also outlines the importance of measuring the baseline ACH using a tracer test (or another method, such as extrapolating ACH data obtained during BPC test; **Section 4**) when possible to support estimation of an upper-end VOC concentration in indoor air, and monitoring indoor-to-subslab ΔPs prior to and during BPC testing when practical for comparison with indoor-to-outdoor ΔP data.

3.2.2 Supply Room

Summary of the Test Outcome

The supply room is a moderately-sized office-type space located within the building. BPC baseline sampling did not identify TCE at concentrations above instrument detection limits; however, TCE was detected during the initial negative ΔP (-5 Pa) and concentrations continued to increase during the subsequent steps (-10 and -15 Pa) to a maximum concentration of 0.72 $\mu g/m^3$ at -15 Pa, by which time the TCE mass discharge had more than tripled relative to the -5 Pa step. The TCE concentrations returned to a level below instrument detection limits upon transition to the positive ΔP step. While the data conclusively demonstrated a complete VI pathway at this location (albeit with modest TCE concentrations in indoor air), the upper-end indoor air concentration was not observed. Long-term VOC monitoring subsequently conducted in this zone during the period May 2019 to May 2020 at a frequency of approximately four samples per day indicated an average TCE concentration in indoor air of about 1.4 $\mu g/m^3$ and a maximum concentration of 13 $\mu g/m^3$ measured in a sample collected in January 2020. Using the worst-case mass discharge from the BPC test and the baseline ACH of 0.21 (measured by tracer testing) produced an upper-bound estimate of 40 $\mu g/m^3$ for this zone. Thus, the mass discharge method provided a somewhat conservative, but useful bounding estimate.

Similar to the test conducted in the office (**Section 3.2.1**), negative indoor-to-subslab ΔPs were measured, but were generally only about one half of the indoor-to-outdoor ΔPs. This provided an indication that the floor system provided relatively little resistance to flow.

During the BPC testing, PCE concentrations increased to as high as 490 $\mu g/m^3$ during the -5 Pa step, then slowly dropped to 13 $\mu g/m^3$ during the subsequent steps. PCE was detected at a range of 0.52 to

6.0 µg/m^3 during the positive ΔP step. Based on prior subslab data collected beneath the building, PCE was known to be present in the subsurface, but at much lower concentrations than TCE. This imbalance in PCE to TCE ratios, as well as differences in the response of TCE and PCE to the ΔP changes, suggested a background indoor source of PCE. Upon further investigation within the larger building outside of the sampling zone, it was discovered that a PCE-containing product was used periodically to clean parts. The long-term VOC monitoring showed how the periodic use of that product in the zone surrounding the supply room produced relatively short-duration spikes in indoor air concentration throughout the building.

Lessons Learned

Similar to the test conducted in the office, this test illustrates that BPC testing is not consistently able to directly observe near worst-case indoor air concentrations. The mass discharge approach can help by providing a useful bounding estimate of upper-end indoor air concentrations.

Review of ΔP data collected during episodes of elevated TCE concentration in indoor air during the monitoring period May 2019 to May 2020 indicates that there is some degree of relationship between indoor-to-subslab and indoor-to-outdoor ΔPs in the supply room, but the data also indicate indoor-to-outdoor ΔP is not a consistently good predictor of indoor-to-subslab ΔP at this location. This would suggest that near worst-case VI conditions could occur under conditions that cannot be directly simulated by BPC (e.g., negative indoor-to-subslab ΔP with relatively neutral indoor-to-outdoor ΔPs). The test results also underline the importance of estimating baseline ACH using tracer testing to assess the degree of envelope leakage during BPC testing, as well as the importance of collecting indoor-to-subslab ΔPs when possible.

This example also illustrates how BPC testing combined with an understanding of VOC concentration distribution in the subslab vapor and surrounding building air can help support data interpretation and differentiate VI from VOC background sources associated with building operations. As noted earlier, experience relative to typical background sources and the VOCs associated with these sources is important to assess BPC test data.

3.3 Warehouse-Type Building at North Carolina Installation

The building is a large warehouse-type structure used for industrial maintenance and repair divided in several large rooms. The BPC test took place in one of these rooms, with a total volume of close to 150,000 ft^3 (the largest test zone volume in this dataset).

Summary of the Test Outcome

Initial VI investigation conducted in the room using evacuated sample canisters identified TCE at concentrations as high as 9 µg/m^3 in indoor air. As a result, it was decided to conduct BPC testing. Similar to the initial investigation, TCE was detected above target level during BPC baseline testing. The TCE concentrations increased to their highest level during the negative -5 Pa step (potentially indicative of near worst-case VI conditions), before decreasing during the -10 Pa step.[9] TCE mass discharge rates calculated based on the TCE concentrations detected at the blower door and the fan air flow rates were observed to increase by close to 60 percent between the -5 and -10 Pa steps. Overall, this dataset supported the conclusion that the VI pathway was complete. Further sampling during BPC showed that multiple cracks in the slab were acting as VI entry points. The TCE concentrations increased significantly at those entry points between baseline conditions and negative ΔPs, an indication that the entry points were likely contributing TCE to indoor air.

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[9] A positive ΔP step was not performed because of analytical instrumentation difficulties and because there was sufficient evidence to conclude that the VI pathway was complete.

Lessons Learned

This BPC test provided another example of the difficulty of interpreting BPC data for large sampling zones and the importance of interpreting the dataset using both concentration and mass discharge concepts as follows:

- The ACHs achieved during depressurization were 0.65 and 1.1 during the -5 and -10 Pa steps, respectively, which does not readily suggest that the room envelope was leaky; however, in consideration of the room size and building age, as well as the lack of a baseline ACH measurement, leakage and dilution effects cannot be excluded and may explain the drop in TCE concentrations observed during the -10 Pa step.
- During BPC testing, indoor-to-subslab differential pressures were measured to be slightly negative, with a magnitude equal to less than one-tenth of the indoor-to-outdoor ΔPs. This would suggest that the slab near the monitoring location was too leaky for indoor-to-subslab ΔPs to change significantly. This could also indicate that more negative indoor-to-subslab ΔPs would result in additional TCE mass migration into the room and that, under certain conditions (e.g., negative indoor-to-subslab ΔPs and neutral indoor-to-outdoor ΔPs), greater TCE indoor air concentrations could be measured that can be achieved during BPC testing.
- Overall, the data show that for large sampling zones, BPC testing can be sufficient to demonstrate the presence of a complete VI pathway but may, in some instance, provide results that, if evaluated on a concentration basis only, might be harder to interpret. For such sampling zones, ACH should be measured under baseline conditions, and indoor-to-subslab ΔPs should be measured at several locations (i.e., several subslab vapor probes) when practical.
- In this case, the combination of increasing mass discharge under increasing degrees of depressurization along with exceedance of the target level during the -5 Pa pressure step provided an adequately actionable dataset (i.e., mitigation is needed).

3.4 Warehouse-Type Building at California Installation B

The building is a large warehouse-type building, in which several office spaces and other rooms are located. The BPC test took place in two connected offices in the middle of the building.

Summary of the Test Outcome

TCE detected above target level in a prior VI investigation using evacuated sample canisters was the impetus for conducting BPC testing in a set of two offices of the building. During BPC baseline sampling, TCE was again detected above the target level with the concentrations increasing during the negative ΔP steps.[10] The mass discharge through the blower door increased by more than one order of magnitude between the two negative steps. Overall, this dataset indicated that the VI pathway was complete, with TCE concentrations exceeding the target level. The spatial pattern of TCE concentrations obtained during the BPC test led investigators to a large hole in the wall above the drop ceiling, which opened to a wall cavity behind the adjacent restroom (**Figure 5**). In the wall cavity, multiple penetrations through the slab to the void space beneath the slab were observed. The void space, which ran beneath a significant portion of the building, had elevated TCE concentrations.

Lessons Learned

This example illustrates how BPC testing was successful at identifying an unusual route for vapor entry (through a drop ceiling and behind a bathroom wall), which conventional VI sampling may not have successfully identified without several rounds of sampling. The ability to depressurize the sampling zone through BPC combined with that of collecting multiple samples with the portable GC/MS instrument

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[10] A positive ΔP step was not performed because there was sufficient evidence to conclude that the VI pathway was complete.

made it possible to assess spatial variability in indoor air concentrations and conclude that the route of vapor entry started overhead. This example also illustrates the importance of relying on experienced personnel to conduct this type of assessment.

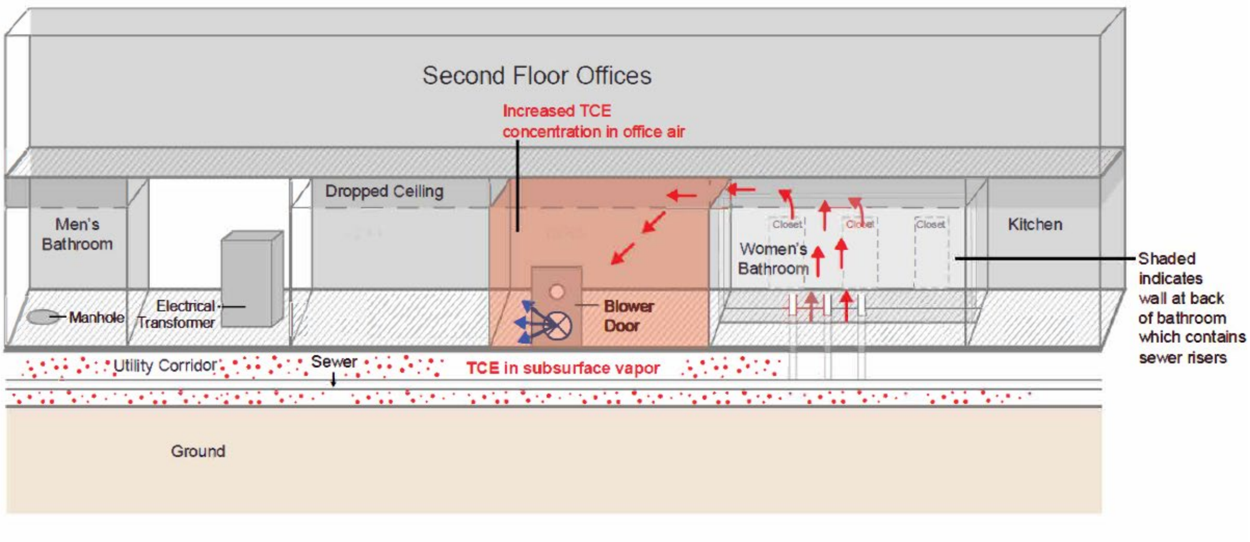

Figure 5. Conceptual model of subsurface vapor transport at the building.

4 BPC Test Recommendations for Data Collection Optimization

This section focuses on providing BPC test procedure recommendations on the basis of the case studies described previously, as well as additional considerations based on literature review and experience from additional tests not described herein.

Define study objectives and identify instances where BPC testing may not be suitable

- The case studies presented in **Section 3** were conducted for one of the following two reasons:
  - In a few instances, BPC testing was conducted as a result of IASL or other target level exceedance identified during an initial VI investigation (via conventional means such as evacuated canisters), with the objective of identifying a cause (e.g., potential background contribution) and/or the location of VI entry points (e.g., perimeter crack, pipe chase)
  - In other instances, BPC testing was conducted without prior VI investigation with the objective of determining the potential presence of a complete VI pathway in one mobilization.

    The latter objective is also associated with the underlying goal of estimating upper-end VOC concentrations in indoor air during testing (near worst-case VI conditions), either through direct observation of concentrations or through estimation on the basis of mass discharge observed during testing. Therefore, it is important to understand the BPC objective prior to conducting the test, as well as potential reasons why this objective may not be met. Additional considerations are provided following.

- Large sampling zones/leaky sampling zones – The case studies described in **Section 3** showed that sampling zone size and leakiness may impact the test outcome. The larger or leakier the sampling zone, the more complicated it will be to achieve and monitor depressurization (i.e., more test time, instrumentation, and uncertainties). In addition, large sampling zones or leaky zones may not be able to successfully achieve near worst-case VI conditions. Although BPC testing may not be sufficient to completely rule out the VI pathway in those instances, it may nonetheless be sufficient to demonstrate that a complete VI pathway exists and that mitigation is warranted (e.g., IASL exceeded during testing with evidence that the exceedance is VI-related). Testing may also be suitable to identify VI entry points. Therefore, BPC testing may have limitations in large or leaky sampling zones, but should not necessarily be ruled out, particularly if VI is suspected.

- Complicated layout and HVAC system – Zones with complicated layouts may not lend themselves to BPC if they have poor air mixing characteristics that cannot be overcome with added mixing fans. In addition, the HVAC system within the sampling zone should be reviewed to understand the degree to which HVAC operation may affect baseline conditions and the results of a BPC test (e.g., HVAC hours of operation if not continuous, positively or negatively pressurized zone, sharing with other zones). Because HVAC operations affect ΔPs, they also impact vapor entry. Therefore, it must be decided prior to running the test whether BPC testing should be conducted with the HVAC system on or off. It is also important to determine if the HVAC system operates with 100 percent air recirculation or introduces fresh air (in which case it would be expected to positively pressurize the space on average). Leaving an HVAC system in operation may unnecessarily complicate BPC testing if the HVAC limits or prevents zone depressurization during testing; however, shutting off the HVAC system may generate conditions that are not representative of VI exposure because for many commercial buildings HVAC operations are required in all seasons to maintain other aspects of indoor air quality and comfort. In addition, making HVAC system shutdown requests may be logistically complicated. Finally, testing outside of typical business hours (e.g., weekend) may occur at a time the HVAC system is not operating and therefore lead to test results that are not representative of occupant exposure.
- Advection- versus diffusion-driven VI – BPC testing assumes that VI is occurring as a result of negative indoor-to-subslab ΔPs, which drive subsurface vapor entry into the building (advection). While experience shows advection-driven VI is most common, the effects of diffusion-driven VI through the slab or openings should not be ignored, particularly if buildings are located on top of a source with elevated VOC concentrations (on the order of hundreds of thousands to millions of $\mu g/m^3$). Diffusion-driven VI is not dependent on indoor-to-subslab ΔP, but occurs on the basis of VOC concentration differences between the subslab and the indoor air. Thus, VOC mass discharge would not be expected to change if diffusion-controlled. In other words, if ACH increased during BPC testing, VOC concentrations would decrease but mass discharge would remain more or less unchanged. If a historical solvent or petroleum source is located under a building and has the potential for elevated subslab vapor concentrations, BPC testing may not respond in the expected way to the effects of diffusion-related vapor transport if these are significant.
- Likelihood of background and potentially confounding sources – In certain circumstances, VOC indoor sources may be mistakenly assumed to be VI-related. As was shown in the case studies, this can occur when the source is located away from the blower door (e.g., drain, closet) and there is sufficient source material to create a VI-like pattern in the BPC testing data. This is most relevant for VOCs that commonly drive VI concerns and are also common background indoor air contaminants (e.g., PCE). Several techniques can be used to identify confounding VOC sources, including the following:
  - Conduct an inventory of products potentially containing VOCs prior to conducting BPC tests and assess the habits of building occupants that may result in the presence of background VOCs in indoor air (e.g., dry cleaning or hobbies/activities with prevalent VOC usage).[11]

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[11] For instance, PCE is commonly found in automotive maintenance products such as brake cleaners or in specialty craft glues. TCE is found in certain firearm cleaners. Additionally, in recent years, the presence of 1,2-dichloroethane in indoor air has been tied to plastic products (Doucette et al., 2010).

  - Assess flow movement (and determine the zone compartments from which flow is coming) when the sampling zone is depressurized during BPC testing.
  - Where possible, use the HAPSITE to measure concentrations of breakdown VOCs during testing. For instance, if PCE or TCE are present in indoor air as a result of VI, cis-1,2-dichloroethene (cDCE) may also be present as a result of subsurface biodegradation. The absence of cDCE does not necessarily rule out VI, especially if there is limited formation of breakdown VOCs in the subsurface and the concentrations in indoor air are too low to detect, but it may provide some indication as to the occurrence of a potential indoor source.

Select BPC sampling zone and define criteria that make sampling zone suitable

The case studies presented in this TM indicate that ideal sampling zones are up to approximately 20,000 ft^3. As indicated previously, tests can be conducted in zones that are greater but may be associated with additional challenges. In some instances, testing an entire building may be desirable, but because of logistical reasons or other considerations (e.g., VI is suspected in a particular area), smaller sampling zones within the building may be selected for BPC. Specific considerations are summarized as follows:

- Sampling zone volume, target flow rate, blower capacity, and test duration – **Figure 6** provides a plot of flow rates and ACH as a function of the volume of the sampling zones that are part of the dataset. The duration of each step can be back-calculated from the ACH. Blower door equipment should be checked to see if it can achieve the desired flow rate. Installation of multiple blower doors, if logistically feasible, may be considered if higher ACHs are desired in larger buildings. Low flow rates may require the installation of rings on the fan to reduce flow rate.[12]
- Occupants, building use, and other related concerns – Running a BPC test can be inconvenient to building occupants because it requires that traffic in and out of the sampling zone be suspended so that external doors are not being opened and closed. Close coordination with building management and its occupants may be needed to meet this requirement. Alternatively, testing may be conducted at night or on weekends when the building or sampling zone is less likely to be occupied. Security concerns at DoD installations, particularly in sensitive-use buildings or areas (e.g., mailrooms, control rooms), may require additional authorization or building escort.
- Leakiness and sampling zone within a larger building ("building-within-a-building" configuration) – Testing of a zone within a larger building can be complicated by the fact that the sampling zone may not be air-sealed relative to the surrounding building to the same extent that a building would be relative to the outside. The sampling zone envelope may be leaky and contain gaps or openings (e.g., overhead utility penetrations) that may not always be visible (e.g., drop ceiling). In addition, VOCs present in background indoor air of the larger building may be introduced into the sampling zone during testing, which will complicate data interpretation, particularly if the indoor source is emitting intermittently. A survey should be conducted to assess the presence of background VOCs within the larger building and to determine if openings can be sealed and/or the test conducted without strong dilution effects. The plots on **Figure 6** show that the smaller the sampling zone, the more elevated the ACH. This is likely because small zones have a larger envelope footprint to volume ratio. In other words, the effects of leakage may be relatively more important in small sampling zones than in large zones.
- Blower door location – Sampling zone configurations often dictate where the blower door can be deployed. To the extent possible, an external door should be used. Note that this is not always

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[12] Energy assessments typically use blower doors to achieve a depressurization of 50 Pa (TEC, 2012; Brennan et al., 2014; Retrotec, 2017). This can result in blower door flow rates that are larger than those needed for VI BPC studies. Smaller blowers designed for duct testing can be used for smaller zones (e.g., Minneapolis Duct Blaster system).

possible for sampling zones within a larger building, though testing using a fan mounted on an exterior window should be considered (McHugh et al., 2012b).[13] As previously noted, blower doors installed at locations leading to the rest of the building may introduce background VOCs from the larger building space during the pressurization step and complicate data interpretation. Note that depressurizing a zone within a larger building may also introduce background VOCs from the larger building through leakage. This can occur even if the blower door is installed on an external door.

- Indoor-to-outdoor ΔP monitoring – In a typical BPC test, indoor-to-outdoor ΔP is monitored at the blower door and at one additional location (e.g., window location with an Omniguard recorder). Additional ΔP monitoring locations may be needed for sampling zones of larger volumes to verify that the readings are representative of the entire zone. As noted previously, wind effects may pressurize one side of the building and depressurize the other side. If the sampling zone is greater than about 10,000-20,000 ft^3, then more than two ΔP monitoring points should be considered, preferably on different sides of the building.
- Indoor-to-subslab ΔP monitoring – Whenever possible (i.e., if subslab vapor probes are present), indoor-to-subslab ΔP monitoring should be conducted during BPC testing for comparison with indoor-to-outdoor ΔP data. Neutral or low indoor-to-subslab ΔPs relative to indoor-to-outdoor ΔPs may indicate that the slab is leaky; however, it may also be an indication that BPC depressurization may not result in near worst-case VI conditions and that other mechanisms may be limiting mass transport (e.g., diffusion from soil). For large sampling zones, multiple indoor-to-subslab ΔP monitoring locations should be considered.
- Presence of potential preferential pathways – Sampling zone selection may need to focus on building areas with potential preferential pathways, such as utility penetration locations (e.g., sewer lines), perimeter walls, etc. Under these circumstances, sampling zones may include such areas as kitchen and breakrooms or bathrooms or other building areas where buried utilities penetrate the buildings.

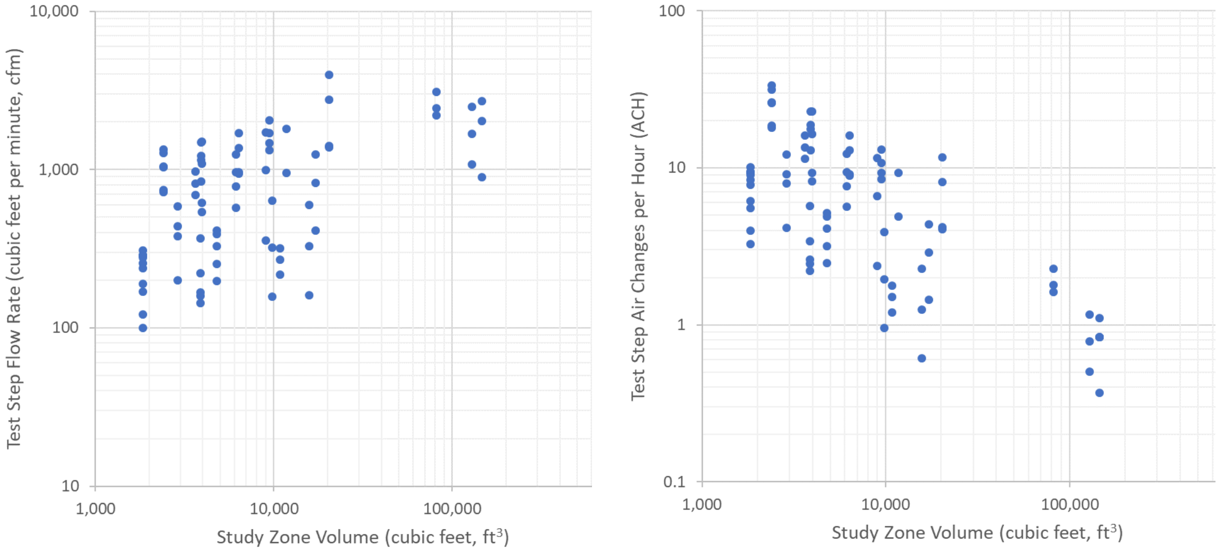

Figure 6. Blower door flow rates and air changes per hour as a function of sampling zone interior volumes for the case studies reviewed in this study.

Each BPC test includes as many points as there are positive or negative ΔP steps.

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[13] This equipment may need to be custom built because it is not commercially available. Additionally, not all buildings have external windows or windows that can be opened by their occupants.

Assessing Ambient Conditions and Establishing Baseline

Conducting baseline monitoring prior to (or possibly after) conducting the BPC test is important to understand test results and demonstrate the representativeness of ΔP selected for testing. The following provides a summary of recommended baseline monitoring practices:

- VOC baseline monitoring – Baseline VOC indoor air monitoring should be conducted under ambient conditions in the sampling zone prior to conducting depressurization or pressurization steps. The VOC data should supplement and be compared to prior data collected during initial VI investigations (if applicable). If background indoor sources are identified during the baseline monitoring, they should be removed (if possible) prior to conducting depressurization or pressurization steps.[14]
- Outdoor air monitoring – Monitoring of outdoor air (as well as building ambient air if the test is conducted in a zone within a building) should be conducted near the blower door prior to and/or after conducting testing to evaluate the potential presence of VOCs in outdoor or building ambient air and their ability to impact test results. If the test is conducted in a zone within a building, additional building ambient air monitoring should be considered after testing if an intermittent indoor source is suspected.
- Tracer testing – When possible, tracer testing should be used to determine baseline ACH (i.e., ACH under ambient conditions). The results should support data interpretation and comparison with ACH values obtained during BPC testing. Tracer testing can be conducted using inert gas, such as sulfur hexafluoride (SF6) or helium. Baseline ACH can also be estimated through extrapolation of ACH data obtained during BPC testing.[15]
- ΔP monitoring under ambient conditions – Test experience shows that at least 1 to 2 weeks of indoor-to-outdoor ΔP monitoring under ambient conditions is needed to obtain enough information regarding the sampling zone and to identify the effects of HVAC operations (and whether it is shut down at nights or during the weekend) and weather patterns (e.g., midday coastal winds). Note that long-term ΔP monitoring experience shows that 1 or a few weeks of monitoring may not fully capture the full extent of seasonal fluctuations in ΔP (e.g., stack effects during the heating season, bay doors closed during the winter); however, several consecutive weeks of monitoring are not anticipated to bring substantially more information than 1 or 2 weeks. Whenever possible (i.e., if subslab vapor probes are present), indoor-to-subslab ΔP monitoring under ambient conditions should also be conducted for review in conjunction with indoor-to-outdoor ΔP data under ambient conditions.

Testing Best Practices

The following guidelines and recommendations are based on review of the case studies presented in this TM:

- Consider three depressurization test steps – Three rather than two depressurization test steps should be used, if time allows, when conducting the depressurization portion of the BPC test. These steps should be representative of observed baseline conditions, but are typically expected to be in the range of -2.5 to -25 Pa. The three depressurization steps can be used to evaluate the changes in VOC concentrations and discharge rate, and evaluate whether near worst-case conditions have been

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[14] This assumes that a portable GC/MS instrument (e.g., HAPSITE) is used to measure VOC concentrations during BPC testing. While such instrument is ideal for BPC testing, it is not always necessary if the objective is not to obtain real-time quantifications of VOC concentrations. Conventional indoor air sampling using evacuated canisters can also be considered during BPC testing, even though there may be limitations in the number of samples collected during testing. Additionally, as noted in **Section 1.3.2**, a PID with ppbv-level detection capabilities (e.g., ppbRAE) can be used to quantify total VOCs (if individual speciation is not needed) and aid in the identification of background indoor sources of VOCs and/or potential entry points for VI.

[15] For example, see ASTM (2019), which requires at least three depressurization steps.

achieved. This approach also allows plotting the ACH and flow rate against the target ΔP, obtaining a regression line through the data points (using the method discussed in ASTM, 2019) and estimating baseline ACH or comparing the results to the baseline ACH obtained via tracer testing. An example of such plot is provided on **Figure 7** for the BPC test presented in **Section 3.2.2**.

- Conduct one pressurization step – One pressurization step (positive indoor-to-outdoor ΔP) should be conducted. The ΔP value should “mirror” one of depressurization steps, i.e., be equal to the absolute value of this depressurization step (generally the smallest step) for comparison of flow rate and VOC data. Buildings that are strongly pressurized or depressurized under ambient conditions will exhibit greater difference in blower door flow rates between the two mirror steps (refer to **Section 3.1.2**).
- Use a minimum of three sampling zone interior volumes during each step – Review of case studies presented in this TM indicates that three air exchanges during a test are sufficient to achieve equilibrium conditions. Studies in the literature suggest that additional air exchange may be needed (Guo et al., 2020 recommend nine air exchanges); however, the case studies presented in this TM do not generally suggest that additional air exchange would lead to greater VOC concentrations. One exception is the test conducted at Building 3280 (**Section 3.1.4**), but additional air exchanges would have extended test duration beyond practical limits and posed some logistical constraints. It would have also been unnecessary as the VI pathway was shown to be complete.
- Configuration of sampling zone and sampling locations – One set of samples must be taken at the blower door (to compute VOC mass discharge) and a minimum of two other indoor air sampling locations should be spaced about the sampling zone. Additional indoor sample locations should be considered for larger or more complex sampling zones. Each of the locations should be sampled at least three times per pressure step to determine if equilibrium has been reached. If not, the step may need to be extended until equilibrium is achieved. Spatial trends in the data should be evaluated during the testing to determine if additional indoor air sampling locations should be added to help identify where potential VI entry points or background indoor sources are located.
- Weather conditions – Conduct test when low wind is expected (e.g., less than 10 miles per hour). It is difficult to achieve and maintain ΔP targets during windy conditions.
- Field data – Use of a field instrument capable of achieving sub-ppbv level detection limits and differentiating VOCs (e.g., HAPSITE) is generally needed to make real-time decisions during BPC testing.[16] A handheld PID (e.g., ppbRAE) can be used in conjunction with the HAPSITE to help quickly pinpoint VOC sources or VI entry points without necessarily spending the time needed to collect and analyze HAPSITE samples.
- Radon – If desired, radon monitoring can be conducted during BPC testing (using, for example, an AlphaGUARD or RAD7 monitor) to supplement VOC concentration data. Radon is a natural tracer of subslab soil gas and can help improve data interpretation (Holton et al., 2015).

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[16] As noted previously, canisters and/or a PID (with ppbv-level detection capabilities) can also be used (with some inherent limitations).

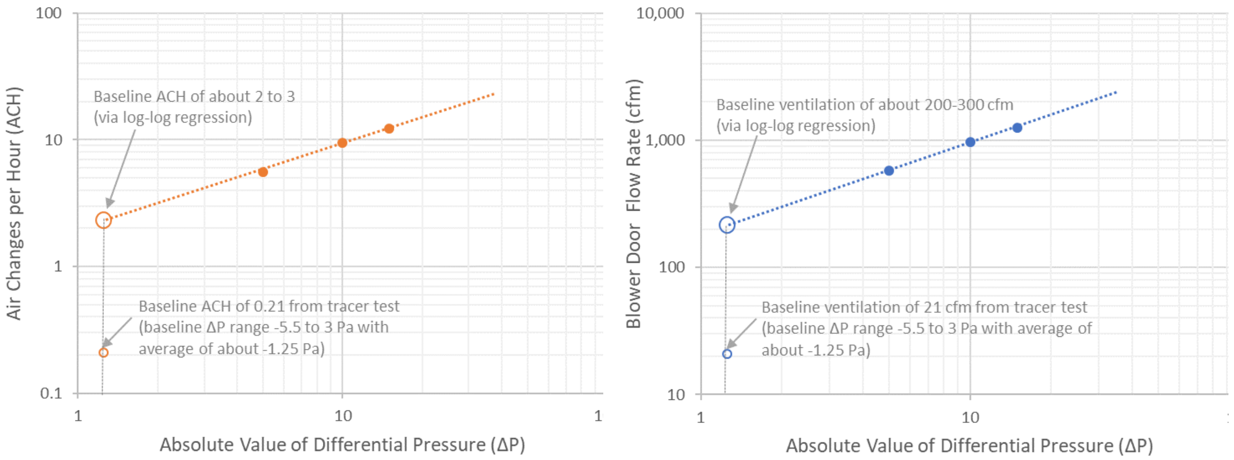

Figure 7. Blower door flow rates and air changes per hour as a function of absolute value of ΔP.

BPC Test Data Interpretation

The following provides recommendations related to BPC test data interpretation:

- Interpretation using observed VOC concentrations in indoor versus VOC mass discharge at the blower door – Refer to **Section 1.3.3** for discussion and estimation of upper-end VOC concentration in indoor air.
- Understanding diffusion-related migration – Diffusion processes cause VOCs within areas of elevated concentrations to migrate to areas of low concentrations. This process governs vapor migration in the deep vadose zone. Near the ground surface, advective processes are thought to drive VOC migration due to the difference between subsurface pressure and indoor pressure. These differences are a result of both changes in barometric pressure (barometric pumping resulting from difference between outdoor pressure and subsurface pressure) and processes within a building that create differences between indoor and outdoor pressures (e.g., stack effects, bathroom and kitchen fans, fume hoods, dryers, HVAC systems). While advective processes may be dominant, diffusive transport cannot necessarily be ignored. The larger the concentration difference between the subsurface and the indoor air, the greater the potential for mass influx; therefore, diffusive transport may be more significant in buildings where historical spills have occurred rather than buildings where VOCs in the subslab results from volatilization of groundwater-dissolved VOCs. BPC testing may not adequately characterize sampling zones where diffusion processes are significant. Diffusion processes across building slabs and/or floor cracks can be evaluated by using flux chambers or similar approaches.
- Other complicating factors – As noted previously, certain indoor sources with sufficient VOC mass located away from the blower door can mimic VI-like conditions. In instances where sampling zones are within a larger building, intermittent use of VOC-containing products within the larger building may create indoor sources within the sampling zone and complicate data interpretation.

5 References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). 2019. *Ventilation for Acceptable Indoor Air Quality*. ANSI/ASHRAE Standard 62.1-2019. October. Accessed May 27, 2020. https://www.techstreet.com/ashrae/standards/ashrae-62-1-2019?product_id=2088533.

ASTM International (ASTM). 2019. *ASTM E779-19, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.* Accessed May 29, 2020. https://www.astm.org/Standards/E779.htm.

Beckley, L., T. McHugh, K. Gorder, E. Dettenmaier, and I. Rivera-Duarte. 2013. *Use of On-Site GC/MS Analysis to Distinguish Between Vapor Intrusion and Indoor Sources of VOCs*. Environmental Security Technology Certification Program (ESTCP), Project ER-201119. November. Accessed May 27, 2020. https://www.serdp-estcp.org/content/download/24416/252911/file/ER-201119-FR.pdf.

Brennan, T., M. Clarkin, G. Nelson, C. Olson, and P. Morin. 2014. *Blower Door Applications Guide: Beyond Single Family Residential.* Edition 1.0. April 1. Accessed May 29. https://energyconservatory.com/wp-content/uploads/2014/07/blower_door_applications_guide_-_beyond_single_family_residential_ver_1-0_0.pdf.

California Department of Toxic Substances Control (DTSC) and California Water Resources Control Boards (WRCB). 2020. *Supplemental Guidance: Screening and Evaluating Vapor Intrusion. Draft for Public Comments.* February. Accessed May 29, 2020. https://dtsc.ca.gov/wp-content/uploads/sites/31/2020/02/Public-Draft-Supplemental-VI-Guidance_2020-02-14.pdf.

Carr, D.B., L.C. Levy, and A.H. Horneman. 2011. Stylistic Modeling of Vadose Zone Transport: Insight into Vapor Intrusion Processes. Presented at Addressing Regulatory Challenges in Vapor Intrusion: A State-of-the-Science Update, 21st Annual International Conference on Soil, Water, Energy, and Air, Association for Environmental Health and Sciences (AEHS), San Diego, CA, March 11-17. Accessed May 27, 2020. https://iavi.rti.org/assets/docs/WorkshopsAndConferences/08_Carr_IAVI_3-9-11.pdf.

Doucette, W.J., A.J. Hall, and K.A. Gorder. 2010. "Emissions of 1,2-Dichloroethane from Holiday Decorations as a Source of Indoor Air Contamination." *Groundwater Monitoring & Remediation*. Vol 30, No. 1. pp. 65-71. Accessed May 21, 2020. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1013.1487&rep=rep1&type=pdf.

Genge, C. 2014. Air Leakage Testing of Commercial Buildings. Presented at the 2014 National Environmental Balancing Bureau (NEBB) Annual Conference, Fort Lauderdale, FL, April 3-5. Accessed May 27, 2020. https://www.nebb.org/assets/1/7/Air_Leakage_Testing_Colin_Genge.pdf.

Guo, Y., P. Dahlen, and P.C. Johnson. 2020. "Development and Validation of a Controlled Pressure Method (CPM) Test Protocol for Vapor Intrusion Pathway Assessment." *Environ. Sci. Technol*. In press.

Holton, C., H. Luo, P. Dahlen, K. Gorder, E. Dettenmaier, and P.C. Johnson. 2013. "Temporal Variability of Indoor Air Concentrations Under Natural Conditions in a House Overlying a Dilute Chlorinated Solvent Groundwater Plume." *Environ. Sci. Technol*. Vol. 47, No. 23. pp. 13347-13354.

Holton, C., Y. Guo, H. Luo, P. Dahlen, K. Gorder, E. Dettenmaier, and P.C. Johnson. 2015. "Long-Term Evaluation of the Controlled Pressure Method for Assessment of the Vapor Intrusion Pathway." *Environ. Sci. Technol*. Vol. 49, No. 4. pp. 2091-2098.

Illangasekare, T., B. Petri, R. Fučík, C. Sauck, L. Shannon, T. Sakaki, K. Smits, A. Cihan, J. Christ, P. Schulte, B. Putman, and Y. Li. 2014. *Vapor Intrusion from Entrapped NAPL Sources and Groundwater Plumes: Process Understanding and Improved Modeling Tools for Pathway Assessment.* Strategic Environmental Research and Development Program (SERDP), Project ER-1687. July. Accessed May 27, 2020. https://clu-in.org/download/issues/vi/VI-ER-1687-FR.pdf.

Lund, L. 2020. Vapor Intrusion (VI) Guidance and Fact Sheets for Indicators, Tracers, and Surrogates (ITS): Reasonable Maximum Exposure (RME) Considerations when Estimating VI Risk. Presented at Why You Should Monitor Indoor Radon, Differential Temperature, and Pressure During Chlorinated Vapor Intrusion Assessments, 30th Annual International Conference on Soil, Water, Energy, and Air, Association for Environmental Health and Sciences (AEHS), San Diego, CA, March 16-19, 2020. Accessed May 27, 2020. https://iavi.rti.org/assets/docs/02_ITS_Guid_Factsheets_Mar2020.pdf.

Lutes, C., C. Holton, J. Kurtz, and R. Truesdale. 2017. Indicators, Tracers and Surrogates: Why Use Them, Probability Analysis, Definitions and Examples. Presented at USEPA VI Workshop: Finding Practical Solutions for the Chlorinated Vapor Intrusion Pathway - Helping RCRA Facilities Meet Significant

Challenges, 27th Annual International Conference on Soil, Water, Energy, and Air, Association for Environmental Health and Sciences (AEHS), San Diego, CA, March 20-23, 2017. Accessed on May 27, 2020 at https://iavi.rti.org/assets/docs/WorkshopsAndConferences/05_AEHS_03.2017_Lutesindicators%20tracers%20and%20surrogates%209%20including%20Holton%20and%20Kurtz.pdf.

Lutes, C.C., C.W. Holton, R. Truesdale, J.H. Zimmerman, and B. Schumacher. 2019. “Key Design Elements of Building Pressure Cycling for Evaluating Vapor Intrusion—A Literature Review.” *Groundwater Monitoring & Remediation* Vol. 39, No. 1. pp. 66-72. Accessed April 8, 2020. https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwmr.12310.

MacGregor, I., M. Prier, D. Rhoda, A. Dindal, and J. McKernan. 2011. *Environmental Technology Verification Report*: *Verification of Building Pressure Control as Conducted by GSI Environmental, Inc. for the Assessment of Vapor Intrusion*. December. Accessed May 29, 2020. https://clu-in.org/download/issues/vi/VI-EPA-600-r-12-007.pdf.

McHugh, T., L. Beckley, and D. Bailey. 2012a. *Protocol for Tier 2 Evaluation of Vapor Intrusion at Corrective Action Sites.* Environmental Security Technology Certification Program (ESTCP), Project ER-200707. July. Accessed May 29, 2020. https://www.serdp-estcp.org/content/download/15883/181700/file/ER-200707-FR.pdf.

McHugh, T.E., L. Beckley, D. Bailey, K. Gorder, E. Dettenmaier, I. Rivera-Duarte, S. Brock, and I.C. MacGregor. 2012b. “Evaluation of Vapor Intrusion Using Controlled Building Pressure.” *Environ. Sci. Technol*. Vol. 46, No. 9. pp. 4792-4799.

Mosley, R.B., D. Greenwell, A. Lee, K. Baylor, M. Plate, and C. Lutes. 2008. Use of Integrated Indoor Radon and Volatile Organic Compounds (VOCs) to Distinguish Soil Sources from Above-Ground Sources. Extended abstract and presentation to the Symposium on Air Quality Measurement Methods and Technology organized by the Air and Waste Management Association (A&WMA), Chapel Hill, NC, November 3-6.

Musielak, M., M.L. Brusseau, M. Marcoux, C. Morrison, and M. Quintard. 2014. “Determination of Chlorinated Solvent Sorption by Porous Material-Application to Trichloroethene Vapor on Cement Mortar.” *Transport in Porous Media* Vol. 104, No. 1. pp. 77-90.

New Jersey Department of Environmental Protection (NJDEP). 2016. *Background Levels of Volatile Organic Chemicals in Homes: A Review of Recent Literature.* Site Remediation Program. August. Accessed May 18, 2020. https://www.nj.gov/dep/srp/guidance/vaporintrusion/vig_background_levels_of_vos.pdf.

Olson, D.A., and R.L. Corsi. 2004. “In-home Formation and Emissions of Trihalomethanes: The Role of Residential Dishwashers.” *J. Expo. Sci. Environ. Epidemiol*. Vol. 14. pp. 109-119. Accessed May 28, 2020. https://www.nature.com/articles/7500295.

Retrotec. 2017. *Operation Manual: Testing Procedures: Residential Pressure and Air Leakage*. Operation Manual Rev-2014-02-15. Accessed May 28, 2020. https://retrotec.com/mwdownloads/download/link/id/5/disposition/inline/.

Schuver, H.J., C. Lutes, J. Kurtz, C. Holton, and R.S. Truesdale. 2018 “Chlorinated Vapor Intrusion Indicators, Tracers, and Surrogates (ITS): Supplemental Measurements for Minimizing the Number of Chemical Indoor Air Samples—Part 1: Vapor Intrusion Driving Forces and Related Environmental Factors.” *Remediation*. Vol. 28, No. 3. pp. 7-31.

Shea, D., C.G. Lund, and B.A. Green. 2010. HVAC Influence on Vapor Intrusion in Commercial and Industrial Buildings. In Vapor Intrusion 2010 Conference of the Air and Waste Management Association (A&WMA), Chicago, IL, September 29-30. Accessed April 14, 2021. https://clu-in.org/download/contaminantfocus/vi/HVAC%20Influence.pdf.

The Energy Conservatory (TEC). 2012. *Minneapolis Blower Door™ Operation Manual for Model 3 and Model 4 Systems*. August. Accessed May 29, 2020. https://energyconservatory.com/wp-content/uploads/2014/07/Blower-Door-model-3-and-4.pdf.

Tri-Service Environmental Risk Assessment Workgroup. 2009. *DoD Vapor Intrusion Handbook*. January. Accessed May 27, 2020. https://clu-in.org/download/char/DoDvihdbk200901.pdf.

Tri-Service Environmental Risk Assessment Workgroup. 2017. *Use of Building Pressure Cycling in Vapor Intrusion Assessment*. DoD Vapor Intrusion Handbook, Fact Sheet Update No. 004, August. Accessed June 29, 2020. https://denix.osd.mil/irp/vaporintrusion/unassigned/fact-sheet-building-pressure-cycling/.

U.S. Army Corps of Engineers (USACE). 2012. *Air Leakage Test Protocol for Building Envelopes*. Version 3. U.S. Army Engineer Research and Development Center. May 11. Accessed May 27, 2020. https://www.wbdg.org/FFC/ARMYCOE/usace_airleakagetestprotocol.pdf.

United States Environmental Protection Agency (USEPA). 1989. *Risk Assessment Guidance for Superfund: Volume I, Human Health Evaluation Manual (Part A)*. Office of Emergency and Remedial Response, EPA/540/1-89/002. December. Accessed May 27, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/rags_a.pdf.

USEPA. 2011. *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990-2005): A Compilation of Statistics for Assessing Vapor Intrusion*. Office of Solid Waste and Emergency Response (OSWER), EPA 530-R-10-001. June. Accessed May 21, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-background-report-062411.pdf.

USEPA. 2012a. *EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings*. Office of Solid Waste and Emergency Response (OSWER). EPA 530-R-10-002. March 16. Accessed May 21, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/oswer_2010_database_report_03-16-2012_final_witherratum_508.pdf.

USEPA. 2012b. *Conceptual Model Scenarios for the Vapor Intrusion Pathway*. Office of Solid Waste and Emergency Response (OSWER). EPA 530-R-10-003. February. Accessed May 26, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/vi-cms-v11final-2-24-2012.pdf.

USEPA. 2015. *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air*. Office of Solid Waste and Emergency Response (OSWER). OSWER Publication 9200.2-154. June. Accessed May 21, 2020. https://www.epa.gov/sites/production/files/2015-09/documents/oswer-vapor-intrusion-technical-guide-final.pdf.

USEPA. 2017. *Documentation for EPA's Implementation of the Johnson and Ettinger Model to Evaluate Site Specific Vapor Intrusion Into Buildings.* Version 6.0. Office of Superfund Remediation and Technology Innovation, September. Accessed April 24, 2020. https://semspub.epa.gov/work/HQ/100000489.pdf.

USEPA. 2018. *Update for Chapter 19 of the Exposure Factors Handbook: Building Characteristics*. Office of Research and Development. EPA/600/R-18/121F. July. Accessed April 24, 2020. http://ofmpub.epa.gov/eims/eimscomm.getfile?p_download_id=536396.

Yao, Y., J. Zuo, J. Luo, Q. Chen, J. Ström, and E. Suuberg. 2019. "An Examination of the Building Pressure Cycling Technique as a Tool in Vapor Intrusion Investigations with Analytical Simulations." *J. Hazardous Materials.* Vol. 389, No. 5.

Attachment A

Building Usage and BPC Test Data Tables

3.1.1 California Installation A – Warehouse-Type Building

Table 1. Building and Zone Details

Building usage	Commercial/Industrial - Warehouse, office space, mail room, and training space
VI Potential	The building lies outside of the 100-foot lateral inclusion zone of a PCE and TCE groundwater plume; however, it may potentially be influenced by preferential VI pathways, such as utility corridors.
Sampling zone location	Office space
Zone selection rationale	TCE was detected below the IASL during the initial investigation under ambient conditions.
Date of test	7/13/2019
Test zone dimensions	3,135 ft^2 x 26 ft ceiling
Test zone volume (ft^3)	81,510
TCE IASL ($\mu g/m^3$)	3

Notes:
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
IASL = indoor air screening level
PCE = tetrachloroethene
TCE = trichloroethene

3.1.1 California Installation A – Warehouse-Type Building

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**	**+5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-4.5	-9.9	6
Actual ΔP achieved (average at secondary location)(Pa)	NA	-9.4	-13.9	1.5
Average ΔP (Pa)	NA	-7.0	-11.9	3.8
Flow rate (cfm)	NA	2444	3086	2208
ACH	Unknown	1.8	2.3	1.6
Approximate duration of each step (minutes)	NA	138	80	60
Mass discharge of TCE (µg/min)	NA	ND	ND	NS
TCE concentration in indoor air (µg/m^3)	0.30 - 1.6	ND	ND	0.32 - 1.1
TCE concentration at blower door (µg/m^3)	ND	ND	ND	ND

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.27 µg/m^3)
NS = not sampled
Pa = pascal
TCE = trichloroethene

3.1.2 California Installation A – Residential Building 1

Table 1. Building and Zone Details

Building usage	Residential - Base housing (apartments)
VI Potential	The building lies above the center of a PCE and TCE groundwater plume.
Sampling zone location	Room Pair/Common Space
Zone selection rationale	PCE was detected above the IASL during initial investigation under ambient conditions.
Date of test	12/5/2018
Test zone dimensions	600 ft^2 x 8 ft ceiling
Test zone volume (ft^3)	4,800
PCE IASL ($\mu g/m^3$)	0.46

Notes:

$\mu g/m^3$ = microgram(s) per cubic meter

VI = vapor intrusion

ft = foot (feet)

ft^2 = square foot (feet)

ft^3 = cubic foot (feet)

IASL = indoor air screening level

PCE = tetrachloroethene

TCE = trichloroethene

3.1.2 California Installation A – Residential Building 1

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-15**	**-20**	**+15**
Actual ΔP achieved (average at blower door)(Pa)	NA	-15.9	-20.1	15.4
Actual ΔP achieved (average at secondary location)(Pa)	NA	-15.9	-21.9	12.1
Average ΔP (Pa)	NA	-15.9	-21.0	13.8
Flow rate (cfm)	NA	198	253	411
ACH	Unknown	2.5	3.2	5.1
Approximate duration of each step (minutes)	NA	80	96	80
Mass discharge of PCE (µg/min)	NA	7.8	11.4	NS
PCE concentration in indoor air (µg/m^3)	ND - 0.39	1.0 - 1.4	1.2 - 1.6	ND

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.34 µg/m^3)
NS = not sampled
Pa = pascal
PCE = tetrachloroethene

3.1.3 California Installation A – Residential Building 2

Table 1. Building and Zone Details

Building usage	Residential - Base housing (apartments)
VI Potential	The building lies above a PCE and TCE groundwater plume.
Sampling zone location	One-room apartment with bathroom
Zone selection rationale	PCE was detected above the IASL during initial investigation under ambient conditions.
Date of test	2/1/2019 and 2/22/2019
Test zone dimensions	230 ft^2 x 8 ft ceiling
Test zone volume (ft^3)	1,840
PCE IASL ($\mu g/m^3$)	0.46

Notes:
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
IASL = indoor air screening level
PCE = tetrachloroethene
TCE = trichloroethene

3.1.3 California Installation A – Residential Building 2

Table 2. BPC Testing Details and Data (Initial)

Target ΔP (Pa)	**Baseline**	**-10**	**-15**	**10**
Actual ΔP achieved (average at blower door)(Pa)	NA	-11.1	-15.6	10.2
Actual ΔP achieved (average at secondary location)(Pa)	NA	-9.8	-14.4	10.2
Average ΔP (Pa)	NA	-10.5	-15.0	10.2
Flow rate (cfm)	NA	100	170	278
ACH	Unknown	3.3	5.5	9.1
Approximate duration of each step (minutes)	NA	85	70	60
Mass discharge of PCE (µg/min)	NA	1.3	1.9	ND
PCE concentration in indoor air (µg/m^3)	ND	0.40 - 0.66	0.71 - 1.0	ND
PCE concentration in closet (µg/m^3)	NS	10	6.9	3.4
PCE concentration in closet (µg/m^3) - adjusted for dilution	NA	10	12	9.5

Table 3. BPC Testing Details and Data (After Background Source Removal)

Target ΔP (Pa)	**Baseline**	**-10**	**-15**	**10**
Actual ΔP achieved (average at blower door)(Pa)	NA	-10.7	-14.8	10.6
Actual ΔP achieved (average at secondary location)(Pa)	NA	-10.6	-15.2	14.1
Average ΔP (Pa)	NA	-10.7	-15.0	12.4
Flow rate (cfm)	NA	122	189	309
ACH	Unknown	3.9	6.2	10.1
Approximate duration of each step (minutes)	NA	57	81	84
Concentrations and mass discharge of PCE (µg/min)	NA	ND	ND	ND
PCE concentration in room (µg/m^3)	ND	ND	ND	ND

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.34 µg/m^3)
NS = not sampled
Pa = pascal
PCE = tetrachloroethene

3.1.4 California Installation A – Instruction Facility 1

Table 1. Building and Zone Details

Building usage	Instruction facility
VI Potential	The building is located within 100 feet of a PCE and TCE groundwater plume.
Sampling zone location	Building wing consisting of approximately 18 rooms.
Zone selection rationale	PCE was detected during initial investigation under ambient conditions.
Date of test	8/10/2019 and 8/11/2019
Test zone dimensions	9,882 ft^2 x 13 ft ceiling
Test zone volume (ft^3)	128,466
PCE IASL (µg/m^3)	2

Notes:
µg/m^3 = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
IASL = indoor air screening level
PCE = tetrachloroethene
TCE = trichloroethene

3.1.4 California Installation A – Instruction Facility 1

Table 2. BPC Testing Details and Data (8/10/19)

Target ΔP (Pa)	**Baseline [a]**	**-5**	**-10**	**5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-4.8	-9.5	4.4
Actual ΔP achieved (average at secondary location)(Pa)	NA	-5.1	-10.3	3.5
Average ΔP (Pa)	NA	-5.0	-9.9	4.0
Flow rate (cfm)	NA	1,079	2,489	1,683
ACH	Unknown	0.5	1.2	0.8
Approximate duration of each step (minutes)	NA	345	169	240
Mass discharge of PCE (µg/min)	NA	147	254	NA
PCE concentration in indoor air (µg/m^3)	1.50 - 5.90	2.10 - 8.10	2.0 - 14.0	ND - 2.30

[a] PCE concentrations in indoor air during baseline sampling on the second day ranged between 2.3 and 40 µg/m^3.

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.34 µg/m^3)
Pa = pascal
PCE = tetrachloroethene

3.1.5 California Installation A – Instruction Facility 2

Table 1. Building and Zone Details

Building usage	Training, offices, warehouse, mailroom
VI Potential	The building lies outside of the 100-foot lateral inclusion zone of a PCE and TCE groundwater plume; however, there is a potential for VI through preferential pathways (utility lines).
Sampling zone location	Mailroom
Zone selection rationale	PCE was detected above the IASL during initial investigation under ambient conditions.
Date of test	5/21/2019
Test zone dimensions	280 ft^2 x 13 ft ceiling
Test zone volume (ft^3)	3,640
PCE IASL ($\mu g/m^3$)	2

Notes:

$\mu g/m^3$ = microgram(s) per cubic meter

VI = vapor intrusion

ft = foot (feet)

ft^2 = square foot (feet)

ft^3 = cubic foot (feet)

IASL = indoor air screening level

PCE = tetrachloroethene

TCE = trichloroethene

3.1.5 California Installation A – Instruction Facility 2

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**	**5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-5.2	-9.9	5
Actual ΔP achieved (average at secondary location)(Pa)	NA	-3.5	-9	5
Average ΔP (Pa)	NA	-4.4	-9.5	5.0
Flow rate (cfm)	NA	691	975	819
ACH	Unknown	11.4	16.1	13.5
Approximate duration of each step (minutes)	NA	123	60	61
Mass discharge of PCE (µg/min)	NA	ND	ND	ND
PCE concentration in indoor air (µg/m^3)	2.10 - 2.50	ND - 0.34	ND	ND

Notes:

µg/min = microgram(s) per minute

µg/m^3 = microgram(s) per cubic meter

ACH = air changes per hour

BPC = building pressure cycling

cfm = cubic foot per minute

ΔP = differential pressure

NA = not applicable

ND = not detected (detection limit of 0.34 µg/m^3)

Pa = pascal

PCE = tetrachloroethene

3.1.6 California Installation A – Instruction Facility 3

Table 1. Building and Zone Details

Building usage	Instruction facility
VI Potential	The building lies outside of the 100-foot lateral inclusion zone of a PCE and TCE groundwater plume; however, there is a potential for VI through preferential pathways (utility lines).
Sampling zone location	Classroom
Zone selection rationale	Chloroform was detected above the IASL during initial investigation under ambient conditions.
Date of test	10/28/2018
Test zone dimensions	1,140 ft^2 x 15 ft ceiling
Test zone volume (ft^3)	17,100
Chloroform IASL ($\mu g/m^3$)	0.12

Notes:
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
IASL = indoor air screening level
PCE = tetrachloroethene
TCE = trichloroethene

3.1.6 California Installation A – Instruction Facility 3

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**	**5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-5.3	-10	5.2
Actual ΔP achieved (average at secondary location)(Pa)	-2.3	-5.4	-9.9	5
Average ΔP (Pa)	-2.3	-5.4	-10.0	5.1
Flow rate (cfm)	NA	411	821	1,249
ACH	Unknown	1.4	2.9	4.4
Approximate duration of each step (minutes)	NA	147	92	98
Mass discharge of Chloroform (µg/min)	NA	3.7	6.7	NA
Chloroform concentration in indoor air (µg/m^3)	0.34 - 0.44	0.28 - 0.39	0.31 - 0.44	0.13 - 0.19
Chloroform concentration at blower door (µg/m^3)	NS	0.27 - 0.39	0.29 - 0.33	0.10 - 0.15

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
NS = not sampled
Pa = pascal

3.2.1 Virginia Installation – Warehouse-Type Building – Office

Table 1. Building and Zone Details

Building usage	Warehouse and Office space
VI Potential	The building lies above TCE groundwater plume.
Sampling zone location	Office
Zone selection rationale	TCE was detected above the rapid action level during the initial VI investigation.
Date of test	3/18/2019
Test zone dimensions	300 ft^2 x 8 ft ceiling
Test zone volume (ft^3)	2,400
TCE RAL ($\mu g/m^3$)	24

Notes:

TCE was detected at 25 $\mu g/m^3$ during initial VI investigation.
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
RAL = rapid action level
TCE = trichloroethene

3.2.1 Virginia Installation – Warehouse-Type Building – Office

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**	**-15**
Actual ΔP achieved (average at blower door)(Pa)	NA	-4.9	-9.1	-13
Actual ΔP achieved (average at secondary location)(Pa)	NA	-6	-12	-17
Average indoor-to-outdoor ΔP (Pa)	0.8	-5.5	-10.6	-15.0
Average indoor-to-sublab ΔP (Pa)	1.2	-3.4	-4.6	-9.3
Flow rate (cfm)	NA	744	1,045	1,267
ACH	0.74	18.6	26.1	31.7
Approximate duration of each step (minutes)	NA	122	105	89
Mass discharge of TCE (µg/min)	NA	156	189	269
TCE concentration in indoor air (µg/m^3)	1.2 - 17	6.2 - 12	5.2 - 11	5.7 - 14

Notes:

µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
Pa = pascal
TCE = trichloroethene

3.2.2 Virginia Installation – Warehouse-Type Building – Supply Room

Table 1. Building and Zone Details

Building usage	Warehouse and Office space
VI Potential	The building lies above TCE groundwater plume
Sampling zone location	Supply Room
Zone selection rationale	TCE was detected above the IASL during the initial VI investigation[a]
Date of test	4/16/2019
Test zone dimensions	510 ft^2 x 12 ft ceiling
Test zone volume (ft^3)	6,120
TCE IASL ($\mu g/m^3$)	0.88

[a] TCE was detected at 1.3 $\mu g/m^3$ during initial VI investigation.

Notes:

$\mu g/m^3$ = microgram(s) per cubic meter

VI = vapor intrusion

ft = foot (feet)

ft^2 = square foot (feet)

ft^3 = cubic foot (feet)

IASL = indoor air screening level

3.2.2 Virginia Installation – Warehouse-Type Building – Supply Room

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**	**-15**	**5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-5.2	-10.8	-16.5	5.8
Actual ΔP achieved (average at secondary location)(Pa)	NA	-5.6	-9.7	-14.9	4.8
Average indoor-to-outdoor ΔP (Pa)	-1.1	-5.4	-10.3	-15.7	5.3
Average indoor-to-sublab ΔP (Pa)	0.2	-2.2	-5.6	-8.2	3.0
Flow rate (cfm)	NA	575	963	1,252	781
ACH	0.21	5.6	9.4	12.3	7.7
Approximate duration of each step (minutes)	NA	100	79	92	87
Mass discharge of TCE (µg/min)	NA	6.7	16	24	NA
TCE concentration in indoor air (µg/m^3)	ND	0.34 - 0.48	0.50 - 0.66	0.64 - 0.72	ND - 0.44
PCE concentration in indoor air (µg/m^3)	ND-0.34	13 - 490	21 - 86	11 - 15	0.52 - 6.0

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.27 µg/m^3 for TCE and 0.34 µg/m^3 for PCE)
Pa = pascal
PCE = tetrachloroethene
TCE = trichloroethene

3.3 North Carolina Installation – Warehouse-Type Building – Maintenance Room

Table 1. Building and Zone Details

Building usage	Former plating shop
VI Potential	The building lies above TCE groundwater plume.
Sampling zone location	Maintenance Room
Zone selection rationale	TCE detected in indoor air above the rapid action level during a long-term monitoring sampling event. [a]
Date of test	3/31/2016
Test zone dimensions	6,480 ft^2 x 22.5 ft ceiling
Test zone volume (ft^3)	145,800
TCE RAL ($\mu g/m^3$)	7

[a] TCE was detected as high as 11 $\mu g/m^3$ during initial VI investigation

Notes:
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
RAL = rapid action level
TCE = trichloroethene

3.3 North Carolina Installation – Warehouse-Type Building – Maintenance Room

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-5**	**-10**
Actual ΔP achieved (average at blower door)(Pa)	NA	-6.9	-10.0
Actual ΔP achieved (average at secondary location)(Pa)	NA	-6.9	-10.0
Average Indoor to Outdoor ΔP (Pa)	-3.5	-6.9	-10.0
Average Indoor to sublab ΔP (Pa)	-0.1	-0.5	-0.9
Flow rate (cfm)	NA	1,567	2,696
ACH	Unknown	0.65	1.1
Approximate duration of each step (minutes)	NA	119	117
Mass discharge of TCE (µg/min)	NA	346	550
TCE concentration in indoor air (µg/m^3)	ND - 9.8	6.0 - 29.5	5.5 - 8.9

Notes:

µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
ND = not detected (detection limit of 0.54 µg/m^3)
Pa = pascal
TCE = trichloroethene

3.4 California Installation B – Warehouse-Type Building – Offices

Table 1. Building and Zone Details

Building usage	Research, operations, and support; assembly; and equipment maintenance, repair, and storage.
VI Potential	Building above TCE/PCE groundwater and soil vapor plumes.
Sampling zone location	Two connected offices in the middle of the building
Zone selection rationale	TCE detected in indoor air above the rapid action level during an indoor air investigation.[a]
Date of test	2/10/2015
Test zone dimensions	1,068 ft^2 x 11 ft ceiling
Test zone volume (ft^3)	11,748
TCE RAL ($\mu g/m^3$)	7

[a] TCE was detected as high as 9.9 $\mu g/m^3$ during initial VI investigation.

Notes:
$\mu g/m^3$ = microgram(s) per cubic meter
VI = vapor intrusion
ft = foot (feet)
ft^2 = square foot (feet)
ft^3 = cubic foot (feet)
PCE = tetrachloroethene
RAL = rapid action level

3.4 California Installation B – Warehouse-Type Building – Offices

Table 2. BPC Testing Details and Data

Target ΔP (Pa)	**Baseline**	**-1**	**-5**
Actual ΔP achieved (average at blower door)(Pa)	NA	-1.2	-4
Actual ΔP achieved (average at secondary location)(Pa)	NA	-1	-4.1
Average ΔP (Pa)	NA	-1.1	-4.1
Flow rate (cfm)	NA	957	1,815
ACH	Unknown	4.9	9.3
Approximate duration of each step (minutes)	NA	96	146
Mass discharge of TCE (µg/min)	NA	67.8	617
TCE concentration in indoor air (µg/m^3)	3.4 - 37.2	2.5 - 126	12 - 1740

Notes:
µg/min = microgram(s) per minute
µg/m^3 = microgram(s) per cubic meter
ACH = air changes per hour
BPC = building pressure cycling
cfm = cubic foot per minute
ΔP = differential pressure
NA = not applicable
Pa = pascal
TCE = trichloroethene