DoD Vapor Intrusion Handbook
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Use of Building Pressure Cycling in Vapor Intrusion Assessment

Purpose

This fact sheet relates to Sections 2.7, 2.8, 3.34, 3.5 and Appendix G of the DoD Vapor Intrusion Handbook. These sections describe methods for indoor air sampling and determining the influence of background sources. Building pressure cycling (BPC) offers an alternative approach to the methods described in the Handbook.

Introduction

Vapor intrusion (VI) can be challenging to assess using conventional discrete indoor air and sub-slab sampling because of spatial and temporal variability in volatile organic compound (VOC) concentrations and background sources of VOC vapors. This can lead to uncertainty in identifying long-term average or short–term (and potentially high end) concentrations due to VI for the occupants of a building.

BPC is an investigation technique that manipulates building air pressure and ventilation to promote or inhibit VI. This is accomplished under several known and uniform levels of building pressure relative to outdoor pressure (Figure 1), with the goal of reducing the uncertainty in indoor air concentrations to tolerable limits. Entire buildings or isolated zones within buildings can be evaluated with this approach using either blower doors, such as used for energy audits, or by manipulation of existing heating, ventilation, and air conditioning (HVAC) systems. Ideally, both cross-building and cross-slab pressure differentials are continuously monitored during the testing. Indoor air VOC concentrations are also measured either: 1) after they have stabilized using real-time monitoring, 2) after three to five times the air volume of the building has been flushed, or 3) after surrogate compounds (such as radon, thoron, or carbon dioxide) have stabilized using real-time monitoring.

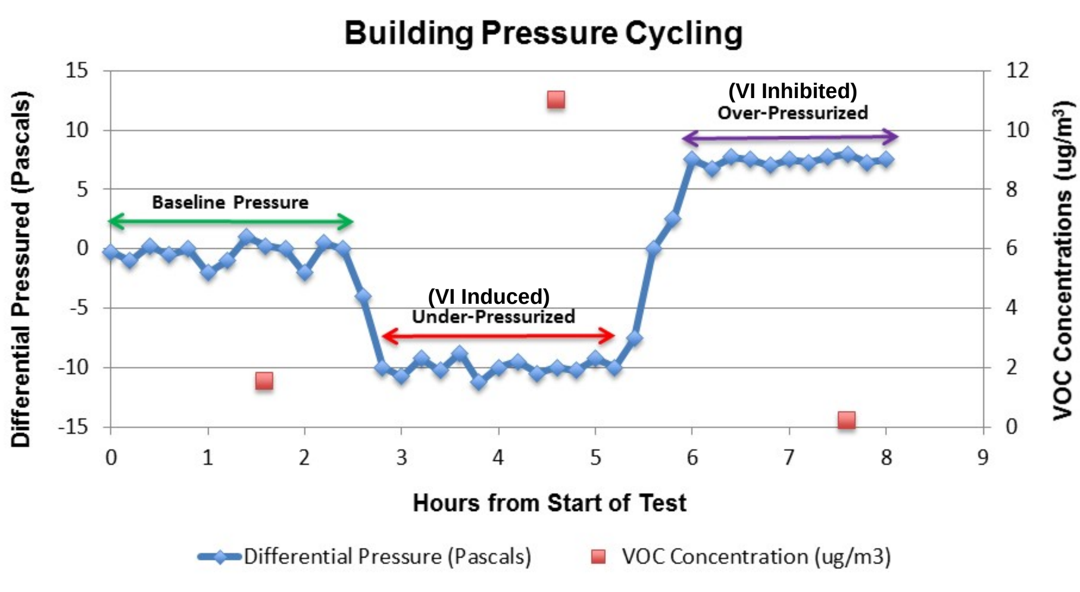

Figure 1: Schematic diagram of building pressure cycling (Courtesy of Geosyntec)

Cross-slab pressure differentials of buildings naturally fluctuate in response to changes in wind speed, outdoor temperature, building heating, cooling, and ventilation conditions, along with activities of the occupants. The range is generally less than $\pm$ 20 Pascals (Pa) and depends on building characteristics (e.g., size, leakiness, HVAC operation, and building uses). These pressure fluctuations induce varying amounts of VI, which leads to temporal variability in VOC concentrations within the building. Some buildings may exhibit generally negative, some generally positive, and others cyclical cross-slab pressure differentials. VI is promoted under negative building pressures and inhibited under positive pressure. Baseline monitoring of the building pressure trends over time is practicable and affordable using micromanometers with data-logging capabilities and is recommended to aid in the design of BPC tests.

Controlling the building pressure substantially reduces the spatial and temporal variability of indoor air concentrations arising from VI compared to indoor air concentrations collected under ambient conditions. Subjecting the building to a series of pressure levels provides building-specific information about the relationship between cross-slab and cross-building pressures as well as between cross-building pressure and building ventilation rates. The product of measured indoor air concentrations and the corresponding building ventilation rates measured at each pressure level provides an estimate of the VI-related mass loading rates. The mass loading rate can be divided by the average building ventilation rate (building volume times air exchange rate) to calculate long-term average building-specific indoor air concentrations attributable to VI for assessment of long-term exposures and risks. Indoor air concentrations measured under negative building pressure provide a potential high-end estimate of indoor air concentrations attributable to VI for assessment of short-term exposures and risks.

Additionally, BPC can be used to identify the presence and contribution of background sources of VOCs to indoor air within a building. VOCs detected in indoor air under positive pressure conditions indicate the presence of background sources. The difference between indoor air VOC concentrations measured under positive and negative pressures induced at similar building ventilation rates provides a measure of the contribution from subsurface sources.

Potential Advantages

- Indoor air concentrations are measured under known and controlled building pressure conditions, which provide more definitive information about the impacts of VI on a building than conventional sampling under ambient conditions.
- BPC provides less uncertainty about indoor air concentrations attributable to VI, which increases confidence in decisions about the potential risk posed by the VI pathway, especially for no further action (NFA) decisions.
- BPC is cost-effective because testing is completed in one sampling event (e.g., approximately 4 to 8 hours) without having to wait for worst-case natural conditions or to conduct multiple rounds of sampling.
- BPC can be used to determine the magnitude of the background contribution to indoor air concentrations in the building by comparing indoor air concentrations under positive and negative pressure.
- The VI-related mass loading from BPC testing can be divided by the average building ventilation rate to estimate indoor air concentrations, or as a benchmark against which to compare the mass removal rate for any mitigation system that may be installed.

Potential Limitations

- Very large leaky buildings may be difficult to depressurize or pressurize, but BPC may be possible for isolated zones within these building.
- Large buildings may be difficult to depressurize or pressurize with conventional blower doors, but existing HVAC systems may be used to manipulate pressures if air inflow and outflow rates can be controlled.
- When using HVAC systems to conduct depressurization tests, compartments within HVAC zones may be difficult to isolate from the remainder of the building.

Application to Risk Assessment and Management

The data obtained through BPC can be used for decision-making about actual and potential future VI impacts at a building, assuming foundation integrity remains similar, by directly comparing indoor air concentrations measured under negative building pressure against applicable indoor air targets for short-term exposures. The mass loading data obtained through BPC testing can also be divided by the long-term average building ventilation rate to calculate long-term average exposure concentrations. Comparison between these two methods for estimating the contribution of VI to indoor air concentrations provides an indication of the uncertainty in the exposure estimate. The goal of BPC is to reduce the uncertainty to tolerable limits. Variability in indoor air concentrations and the mass loading estimates determined through BPC is likely to be less than a factor of five based on data collected to date.

Comparison of Indoor Air Concentrations Measured during Depressurization to Target Levels for Short-Term Exposures

Comparison of indoor air concentrations to target levels should ideally be made after the influence of background emissions (determined when building is under positive pressure) is accounted for and when the building is under negative pressure. Indoor air concentrations measured under positive pressure represent background, and the difference between concentrations measured under negative versus positive pressure is indicative of potential high end short-term exposures. The indoor air concentrations measured at the upper end of the natural depressurization range likely represent high end exposures and, therefore, likely overestimate VI risks from long-term average exposures.

If the indoor air concentrations induced under negative building pressure pose no significant risk (e.g., are below conservative risk-based screening levels or cumulative risks are below targets), the assessment can be concluded with NFA with a higher degree of confidence than with current indoor air quality sampling methods. If the induced concentrations fall between risk-based screening levels and project-specific action levels used for site risk management decisions, mitigation may be warranted and/or further assessment may be conducted. This could include continued pressure monitoring to better understand long-term building conditions or targeted investigation to better identify the points and conditions of vapor entry. If the induced indoor air concentrations are above project-specific action levels, mitigation likely is warranted.

Comparison of Measured Indoor Air Concentration Calculated from Mass Loading Measurements to Target Levels for Long-Term Exposures

The VI-related mass loadings measured by BPC testing can be divided by conservative, long-term, average building ventilation rates to provide estimates of long-term average indoor air concentrations for comparison to target concentrations for long-term exposures. The product of the measured indoor air concentrations and ventilation rates (at each depressurization step if multiple steps are performed) provides a measure of the total mass loading through the building. The VI-related mass loading can be determined by subtracting the mass loading contributed by background sources (determined under positive building pressures).

Technology Description

BPC is a commonly applied technology for building energy audits [link to ASTM 1827-11] that recently has been applied to VI investigations (McHugh, 2008; McHugh et al.,2012; Guo et al., 2015; Holton et al., 2015). For energy audits, a fan (window fan, blower door, or air handling unit [AHU]) is used to under-pressurize or over-pressurize the interior of a building and the building envelope pressure differentials and fan flow rates are recorded for a series of building pressure conditions. Regression analysis of the measured building envelope differential pressures and flow rates yields a building-specific leakage curve (Figure 2), which can be used to estimate the ventilation rate of the building for ambient average (or any other) pressure conditions. Building pressure differentials tested for energy audits range up to ± 75 Pa, which greatly exceeds the natural range of most buildings. If the ambient cross-building pressure differential is measured, the ambient air exchange rate can be estimated via extrapolation of the trend measured during BPC testing.

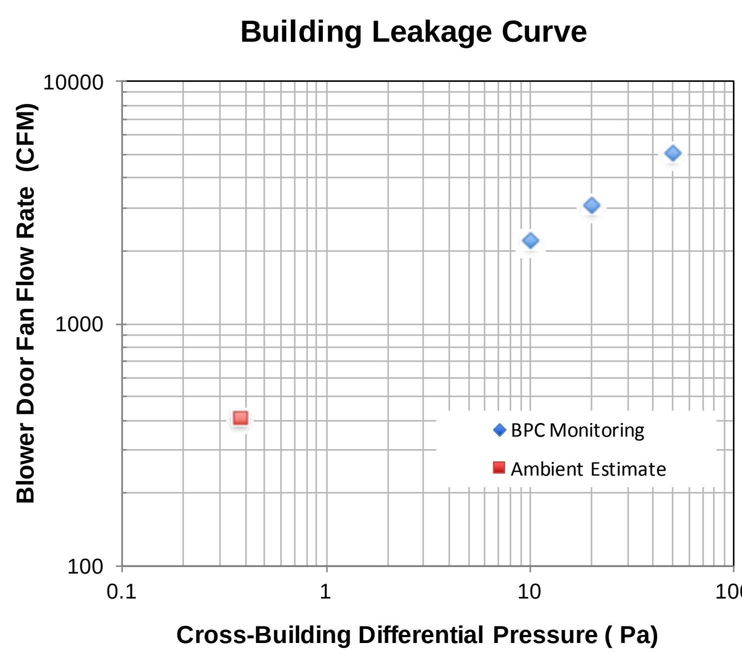

Figure 2: Example building leakage curve (Courtesy of Geosyntec)

Residential buildings generally have either central furnaces and air conditioners or have room-by-room heating and cooling (e.g., radiators or baseboard heaters, in-window air conditioners). Large buildings usually have HVAC systems, which include AHUs that blow air into the building, and exhaust fans at washrooms and kitchens (also sometimes fume hoods, paint booths, etc.) and ductwork that distributes air supply and return throughout the building. BPC testing with a blower door is usually sufficient for single-family residences. Large door fans are available for large buildings, but because they are less readily available or difficult to deploy it is often easier to engage a qualified HVAC professional to manipulate building pressure by adjusting the exhaust and make-up air flow rates.

For VI applications, the BPC test is conducted as for energy audits, with the addition that indoor air samples are collected after concentrations stabilize. This may be after sufficient air exchanges have occurred (3 to 5 air exchanges should be sufficient if box fans are used to promote mixing of the indoor air). Indoor air concentrations may also be monitored in real time during each pressure step to demonstrate that concentrations have stabilized. Cross-slab and cross-building pressure differentials also are monitored continuously throughout the test. Under a series of controlled pressure steps, a building-specific response curve can be prepared by plotting the average cross-slab pressure differentials (which drives vapor entry) versus average cross-building pressure differentials (which are correlated with building ventilation rates). This plot can be used to estimate cross-building pressure differentials under ambient average or other pressure conditions (Figure 3). In combination with the building leakage curve (Figure 2), this provides a means of estimating building-specific ventilation rates for any given average ambient cross-slab pressure differential.

Building depressurization is conducted to promote vapor entry through building foundation cracks, openings, and other vapor entry points, followed by building pressurization if background sources of the VOCs of concern are anticipated. The difference in the concentrations of VOCs in the indoor air samples collected during over- and under-pressurized conditions with comparable building air exchange rates represents the contribution of vapors from the subsurface. If pressurization is conducted first, the time required for concentrations to stabilize under depressurized conditions would be extended, which adds to the cost.

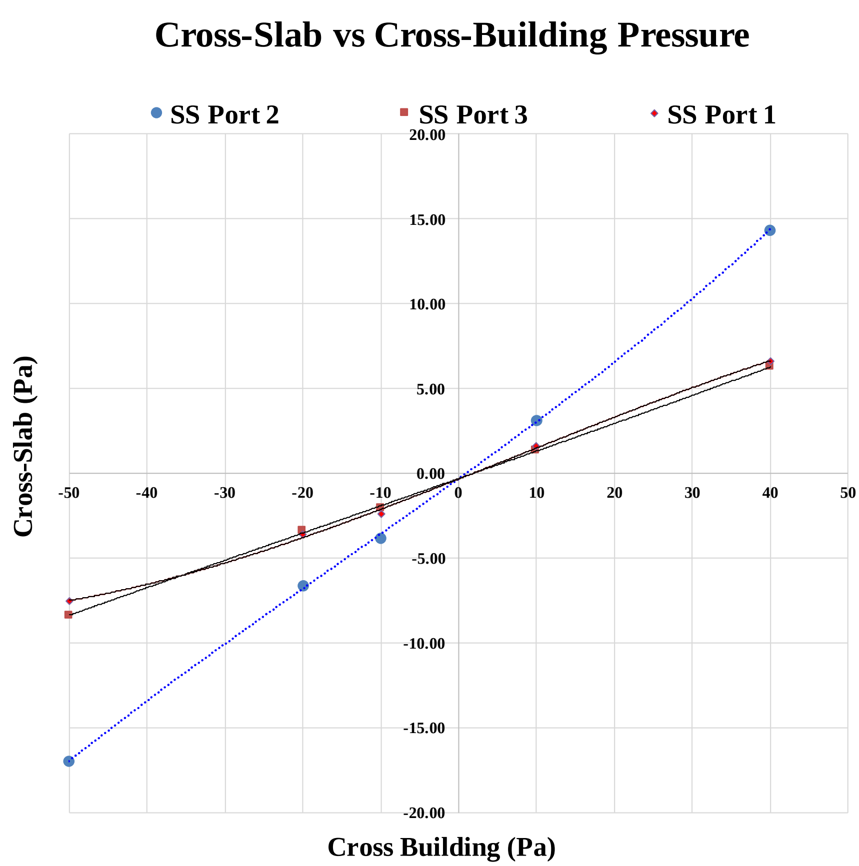

Figure 3: Cross-slab pressure differentials as a function of cross-building envelope pressure differentials (Courtesy of Geosyntec)

The cross-building envelope pressure differentials and induced cross-slab pressure differentials can be easily characterized by using tubing to connect micromanometers with data-logging capabilities to openings through the building envelope (cross-building) and to well-sealed sub-slab probes (cross-slab). Cross-building pressure differentials may be biased by localized wind loads on the exterior wall of the building, which can be addressed by running tubing to some distance from the building and covering the opening with foam to attenuate gusts. Buildings may be very leaky and show very minimal pressure fluctuations or relatively air-tight, in which case even small changes in flow into or out of the building can cause positive or negative building pressures. BPC for VI assessment should include testing over the natural range of building pressure conditions to provide realistic results. The natural range of building pressures varies greatly from building to building, but generally is less than ±20 Pa based on data collected to date. There is value, however, in testing pressure differentials larger than the natural range, as higher pressure differentials improve the definition of building-specific leakage curves. The entire range of pressure conditions can be tested in a single event of BPC, conducted over one day.

Pressure testing at more than one level is recommended because it provides valuable information about the response of the building to varying depressurization/ventilation levels and their associated influence on VI mass loadings and indoor air concentrations. Understanding these relationships improves confidence in risk management decisions about the potential VI impacts on the building. Excessive depressurization can result in excessive dilution by the forced inflow of outside air through the building envelope. Insufficient depressurization may not induce the mass loadings that will pose the greatest risk to occupants. Demonstrating an understanding of the trade-off between forced mass entry and excessive dilution is important for regulatory acceptance.

Considerations for Building Pressure Control Implementation

Successful implementation of BPC for VI assessment requires consideration of the building size, test design options (including options for pressure manipulation in the building, pressure differentials to test, locations to measure pressure differentials, and timing of the tests), methods of indoor air and outdoor air monitoring, methods for determining building ventilation (or air exchange rates) during the test, and methods for determining potential vapor entry points. Each of these is discussed below.

- Building size:
  - Influences the time needed to flush a building multiple times at the ventilation rate needed to induce a certain negative or positive pressure.
- Test design considerations:
  - Health and safety issues:
    - Inducing upper-bound, VI-related, indoor air concentrations may result in exposures of health concern to building occupants, and measures to minimize or preclude exposing building occupants should be implemented. These may include:
      - Conducting the testing over as short a time as feasible;
      - Conducting the testing when the building is unoccupied (on the weekends or holidays); or
      - Ensuring adequate ventilation of the building prior to reoccupation to reduce induced concentrations to natural levels.
  - The use of a field portable chemical detector for indoor air monitoring may be used to identify the presence of background sources of VOCs or vapor entry points.
  - Pressure manipulation options:
    - Blower door for smaller buildings (easy to implement; standard test methods available).
    - HVAC manipulation for larger buildings (may be the only practicable approach and generally requires consulting or engaging a qualified HVAC professional).
  - Pressure differential(s) to test:
    - At a minimum, one level of pressure differential should be tested (negative and positive, if background sources are suspected).

        - Because of uncertainty in the building response to pressure manipulation, it is beneficial to test more than one pressure differential to ensure the building's responses (i.e., ventilation rates) to the range of natural pressure conditions the building may experience are understood.
    - Differential pressure measurements:
        - Digital micromanometers with data-logging capability are preferred due to the ability to continuously monitor and record pressure differentials.
        - Cross-building envelope pressure differential is a standard measurement for blower door applications.
        - Measuring cross-slab pressure differentials concurrently with cross-building envelope pressure differentials is essential to understanding the influence of building pressure conditions on vapor entry, the resulting indoor air concentrations, and the mass loading from the subsurface into the building.
        - It is also useful to temporarily deploy a weather station to concurrently measure wind speed and direction, barometric pressure, and indoor and outdoor temperatures. Nearby airports may also provide useful data.
    - Timing of test – Ideally testing is conducted when the building is not occupied to:
        - Ensure occupants are not exposed to elevated indoor air concentrations that may arise during the tests;
        - Minimize disruption to occupants; and
        - Minimize influence of occupant activities on sample collection.
- Indoor air monitoring options during test:
    - Discrete monitoring (limited time period samples, e.g., 15- to 30-minute Summa™ grab samples) collected upstream of the blower door or fan outlet(s) to provide a volume integrated indoor air sample when the building is depressurized.
    - Spatially-integrated monitoring (equivalent to composite sampling of indoor air) achieved by mixing indoor air with fans, or collecting composite samples using a mobile sampling approach. This approach is needed for indoor air sampling when pressurizing the building.
    - Indoor air monitoring with a field portable chemical detector over time can allow for real-time decision making, but also adds significantly to cost. It is a useful screening tool for demonstrating that VOC concentrations have stabilized prior to taking "definitive" indoor air samples (i.e., via Summa™ canisters).
- Outdoor air monitoring during test:
    - Provides measure of any background ambient air sources of VOCs of interest.
    - Ideally collected as time integrated samples at locations upwind of buildings and/or near building air intakes if HVAC includes AHUs.
- Determining building ventilation (or air exchange) rates:
    - Building ventilation rates are continuously monitored during BPC with blower doors and the flow rate data are used to develop a building-specific leakage curve.
    - HVAC system flow rates are measured including the proportion of make-up air that enters the system during the test.
    - Tracer tests may be used as a verification method to compare to blower door rates or where HVAC operating parameters are not well defined. It may be difficult to obtain reliable tracer data due to incomplete mixing of tracers in indoor air.
- Identify potential vapor entry points:
    - Smoke pens or soap bubbles can be used for visualizing cross-slab flow and building air currents.
    - Thermal imaging cameras can potentially identify points of soil vapor entry.

- Screening floor penetrations with photoionization detectors (PIDs), flame ionization detectors (FIDs) or gas chromatography (GC) field portable chemical detectors under negative pressure can identify vapor entry points where VOCs are elevated relative to ambient levels.

Keys to Data Quality

- Experience with this technology is critical for successful applications. It is important that trained practitioners conduct the tests.
- Pressure can be controlled using fans, but selection depends on the size of the building/room. Blower door fans are usually sufficient for buildings up to about 10,000 ft^2. HVAC system adjustments are best for large buildings, which require input and assistance from qualified HVAC professional(s) responsible for HVAC operations.
- Building pressure or vacuum should be compared to wind speed, temperature and barometric pressure to determine the magnitude of wind load and stack effects on the building.
- Building depressurization tests should be conducted at several different depressurization levels to determine the level at which vapor entry is enhanced without overly diluting indoor air concentrations by excessive ventilation. Predicting the appropriate pressure/vacuum level (or levels) is one of the areas where further improvement is needed.
- Cross-slab pressure differentials should be continuously monitored to demonstrate that the pressure or vacuum applied during BPC testing is sufficient to overcome natural fluctuations.
- Representative indoor air samples should be collected after flushing 3 to 5 building or zone volumes and using box fans to mix the indoor air to promote stable concentrations. Alternatively, continuous monitoring of VOCs or surrogates (radon, thoron, CO_2, temperature, humidity, etc.) can be used to determine when near steady-state conditions have been reached after a change in pressure differential.
- Under depressurization, a sample collected at the upstream face of the exhaust fan provides a volume-integrated indoor air sample.
- Under positive pressure, it is somewhat more challenging to collect a representative volume-integrated sample. Fans can be used inside the building to mix the air to minimize spatial variability. Samplers are best placed at air exhaust points (windows, doors, vents, etc.) rather than immediately adjacent to the blower door or HVAC unit being used to pressurize the building. Alternatively, a spatially averaged sample can be collected by using a mobile, real-time monitoring approach to sampling various locations within a building.
- Collect concurrent outdoor air samples to identify the contribution of ambient air to indoor air.
- Consider determination of the existence of extraneous VOCs or semi-volatile organic compounds (SVOCs) contributors by using a chemical identification system (e.g., HAPSITE). If other sources are found, document and remove if possible.

Future Research

Research is ongoing regarding how best to conduct BPC in buildings of various sizes, determine the temporal variability in BPC results across seasons, and use the results for risk assessment and risk management at VI sites [link to ESTCP ER-201503].

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