DoD Vapor Intrusion Handbook
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High Volume Soil Gas Sampling for Vapor Intrusion Assessment

Purpose

This fact sheet prepared by the Department of Defense (DoD) Tri-Services Environmental Risk Assessment Workgroup (TSERAWG) relates to Section 3.3.3 and Appendix D of the DoD Vapor Intrusion Handbook, and reflects application of new technologies for vapor intrusion sampling.

Introduction

High volume sampling (HVS) is a method for assessing vapor concentrations and distributions in the subsurface, and is particularly well suited to sub-slab soil vapor sampling as part of a vapor intrusion (VI) assessment. The technique involves removing a large volume of gas from below the concrete floor slab (e.g., 10,000 to 100,000 L), and monitoring the organic vapor concentrations and pneumatic response for analysis and interpretation of the vapor distribution between and beyond the point(s) of suction. The HVS method provides more information than traditional discrete sub-slab soil gas sampling, and is faster, less expensive and less disruptive (especially in large buildings). The concentrations measured in the extracted gas can be used for compound ratio analysis to assess background sources or adjusted to account for leakage across the floor slab and compared to building-specific sub-slab screening levels to help assess the potential for health risks. HVS tests also provide design data for mitigation systems that may be required to manage risks.

Potential Advantages

- Lower risk of a false negative outcome (failing to identify an area of elevated vapor concentrations)
- Fewer investigative locations (simplifies access, minimizes disruption, expedites the assessment)
- Can be used to calculate a building-specific attenuation factor
- Can capture sub-slab vapor from under restricted access areas
- Provides a measure of the leakage of the floor slab to support decisions regarding whether floor sealing is useful
- Can identify presence of atypical preferential pathways via analysis of pneumatic and tracer test data
- Provides data for optimal sub-slab venting system design

Potential Limitations

- Buildings with slabs on clay-rich or wet soils can yield very low flow rates, which could render the HVS test method ineffective
- Flow to the suction point may not be radial if the material below the floor slab has irregular permeability (this can be assessed using vacuum monitoring points in different directions)
- Special considerations for safety are required if methane is present below the floor slab near the explosive range (5 to 15% v/v), or higher
- The effluent gas may need to be treated (e.g., carbon filtration) if the building is too large to allow for a discharge hose to be run through an exterior door or window

- Greater equipment requirement than conventional sub-slab sampling
- Best performed during hours when building occupants are absent (evenings and weekends)

Keys to Data Quality

- Verify the integrity of seals in the equipment
- Instrument calibration and maintenance
- Complementary lines of evidence (O_2, CO_2 and CH_4 concentrations, steady and transient vacuum, tracer tests, building plans and sections, visual inspection of material below the floor, geologic setting)

Rationale for High Volume Sampling

Conventional sub-slab samples for VI assessment are typically 1 L or less, and therefore represent a "point-measurement" of the sub-slab vapor concentrations. Spatial variability concerns have resulted in regulatory guidance to collect multiple samples, and at spacing as close as every 2,500 ft^2 or less. For large buildings, this either results in a large number of samples (which is costly and disruptive) or an increasing potential for missing areas of elevated concentrations between progressively widely-spaced samples. HVS was developed to minimize the risk of failing to identify localized hotspots, and minimize the number of investigative locations (McAlary et al., 2010; Lewis et al., 2004).

Technology Description

HVS consists of drawing gas from below the floor at high flow rates (typically 10 to 100 standard cubic feet per minute [scfm]) for 30 to 90 minutes, which draws sub-slab gas from progressively larger distances over the duration of the test. HVS equipment consists of a fan (or blower or vacuum) connected to a cored hole in the concrete floor, as shown in Figure 1. The flow velocity is measured (e.g., via pitot tube or thermal anemometer) in a linear segment of pipe long enough to minimize turbulence (roughly 10X the diameter). A sampling port and a vacuum gauge are set as close as possible to the point where gas is extracted from the floor. The pipe is sealed to the floor with an air-tight seal (e.g., quick setting anchor cement).

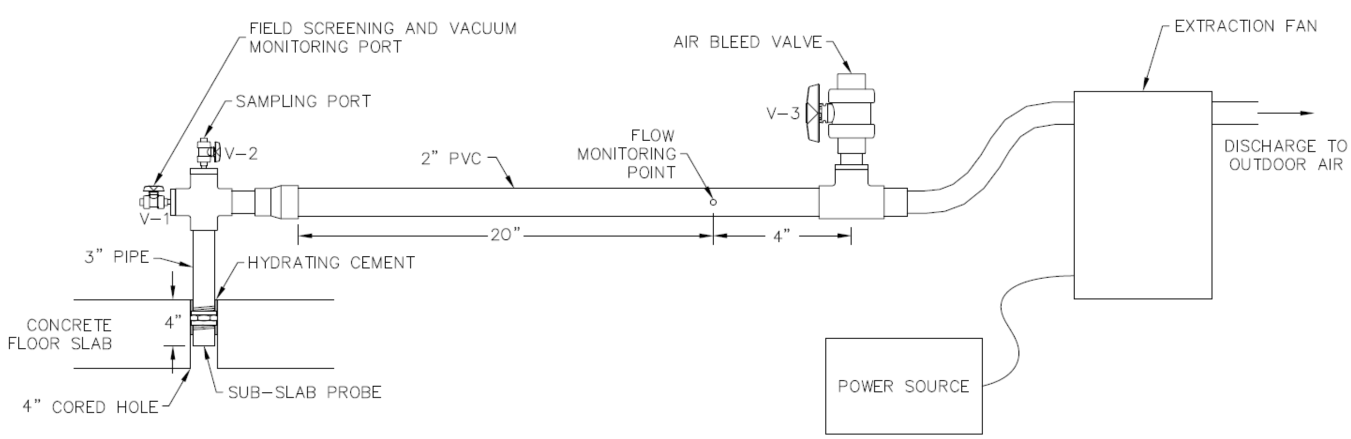

Figure 1: Schematic diagram of HVS test equipment (Courtesy of Geosyntec)

Real-time monitoring of the extracted gas is conducted with common portable instruments. A landfill gas meter measures oxygen (O_2), carbon dioxide (CO_2) and methane (CH_4) concentrations, which are often distinctly different in soil gas compared to indoor air. Therefore, monitoring fixed gas concentrations over the duration of an HVS test provides an indication of the amount of indoor air leakage into the sub-slab region during the test. A photoionization detector (PID) or flame ionization detector (FID) is used to measure total volatile organic compound (VOC) vapor concentrations. Field screening can easily be performed several times during the HVS test, so the trend of field screening readings can be assessed as a function of the volume purged. Samples for laboratory analysis can also be collected at the beginning and end of the test to assess whether and to what degree concentrations of specific compounds changed in response to drawing gas from greater distances from the suction point.

Pneumatic testing (vacuum and flow measurements) provides a very valuable additional line of evidence for the assessment and potential mitigation of VI. Steady-state (vacuum versus distance) and transient (vacuum versus time) measurements are easily added at the end of an HVS test. These data can be analyzed using the Hantush-Jacob (1955) Leaky Aquifer Model (see the Technical Appendix), after making adjustments for the differences in density and viscosity between gas and water. This yields the transmissivity of the material below the floor slab and the leakance of the floor slab, which can be used with simple spreadsheet calculations to derive the profiles of vacuum, velocity, travel time and proportion of leakage across the floor as a function of radial distance from the suction point. This information provides a second line of evidence to compare to the O_2/CO_2 data for assessing the impact of leakage across the floor slab. Quantifying the leakage of indoor air during the test provides a basis for mass balance calculations to correct for the dilution of the HVS samples prior to comparing the sub-slab concentrations to building-specific screening levels. The pneumatic analysis also provides information to help select the number and spacing of suction points for a full-scale mitigation system (if needed).

Optional tracer testing (using a gas such as helium) provides another valuable additional line of evidence to independently verify the gas velocity below the floor. This can be performed using an inter-probe test (inject helium in a sub-slab probe and monitor the arrival at the point of extraction), or using a flood test (reverse the flow direction after the test and add helium to the injected air and monitor the arrival of helium at sub-slab probes surrounding the point of injection). A separate fact sheet is available that provides details on tracer testing [link to TSERAWG 2017].

After completion of the testing, the cored hole and all communication test points are sealed with a durable, air-tight seal (e.g., fast-setting anchor cement).

HVS Data Interpretation

The HVS data can be used to infer the spatially-averaged sub-slab concentrations, infer the vapor distribution between and beyond the suction points, and assess whether the conditions match the simplifying assumptions in the mathematical model. A mass balance calculation on the O_2 and CO_2 data provides evidence for the dilution attributable to indoor air leakage across the floor slab and can be used to calculate the true volume-averaged sub-slab concentration prior to dilution. This can be compared to building-specific sub-slab screening levels calculated using the indoor air screening level and a building-specific attenuation factor (Equation 8 in the Technical Appendix).

If total VOC screening readings are observed to increase significantly during a HVS test, this indicates an area of elevated concentrations is nearby. A hammer-drill can be used to create temporary probes in various directions from the HVS suction point to navigate to the area of concern, so it can be pinpointed in real time. In cases where the measured transient and steady vacuum data and the tracer test data all match the mathematical model, there is strong support for a relatively uniform, homogenous, isotropic material below the floor and radial flow to the suction point. Where there are differences between the field data and the model, the differences provide clues regarding the presence and location of atypical conditions below the floor, such as atypical preferential pathways.

Example Data

Typical VOC data from several HVS tests are shown on Figure 2. Some locations show consistently high concentrations, indicative of a strong vapor source beneath the building. Some show consistently low concentrations, indicative of a weak vapor source. Some locations show gradual decreases in VOC concentrations with volume purged (potentially attributable to dilution from leakage across the floor), but some locations show an increase in concentrations, indicating there are higher vapor concentrations at some distance from the point of suction, which can be used to seek and pinpoint localized vapor sources below the building.

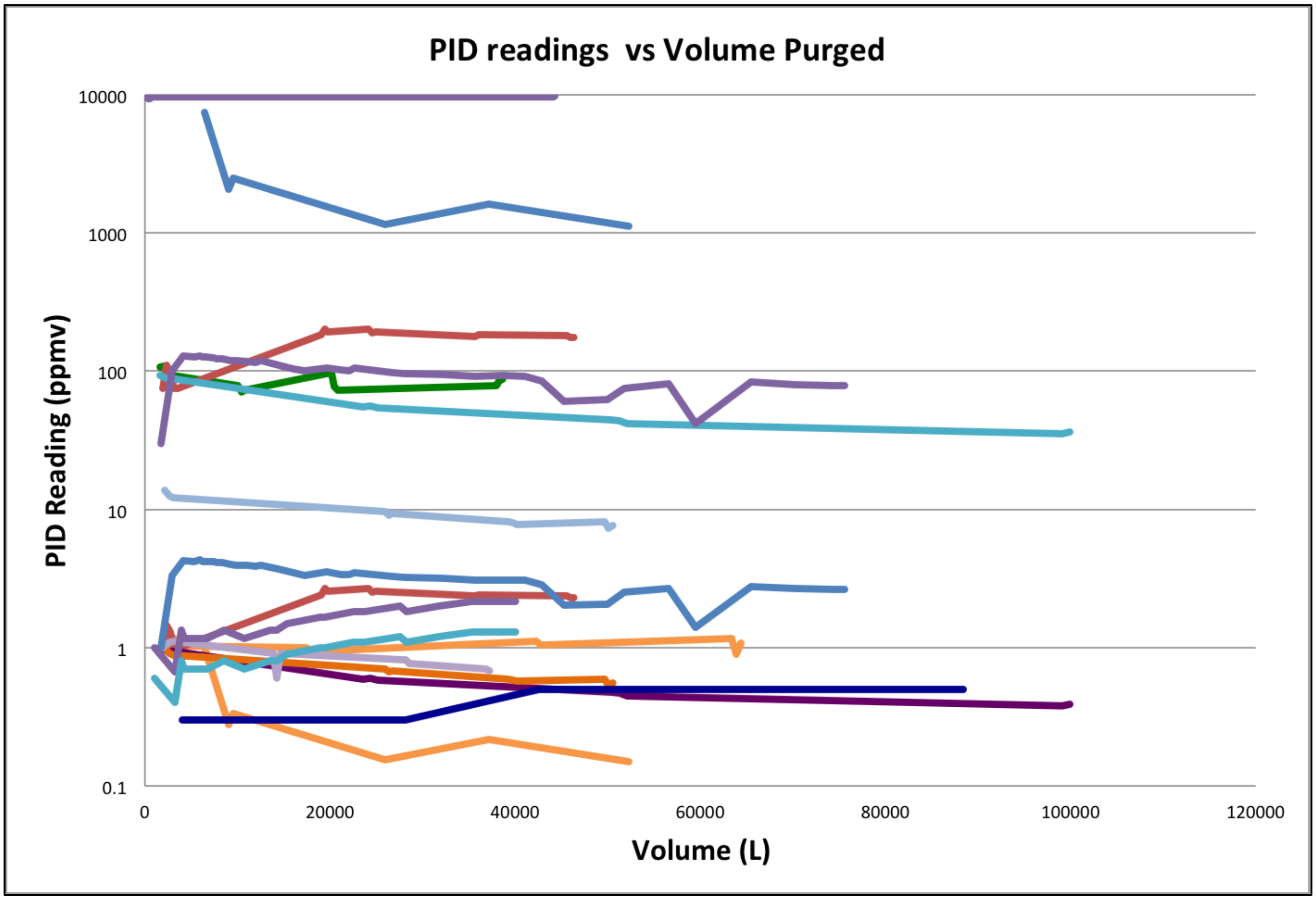

Figure 2: Typical PID readings from HVS tests (Courtesy of Geosyntec)

Example O_2 and CO_2 data are shown on Figure 3. Locations with the highest CO_2 concentrations had the lowest oxygen concentrations and vice versa, which is typical when aerobic degradation of hydrocarbons is occurring in the subsurface. All of the locations showed elevated CO_2 (compared to average outdoor air at 0.03%) and all locations showed O_2 levels below atmospheric (21%), although one location rose to that level by the end of the test. The data show a modest increase in O_2 and decrease in CO_2, which is consistent with air leakage across the floor slab, but the rate of change is very slow, indicating the slab is not very leaky. A mass balance calculation can be performed to calculate the percent leakage assuming the indoor air concentrations of O_2 and CO_2 are 21% and 0%, respectively, as a reasonable approximation.

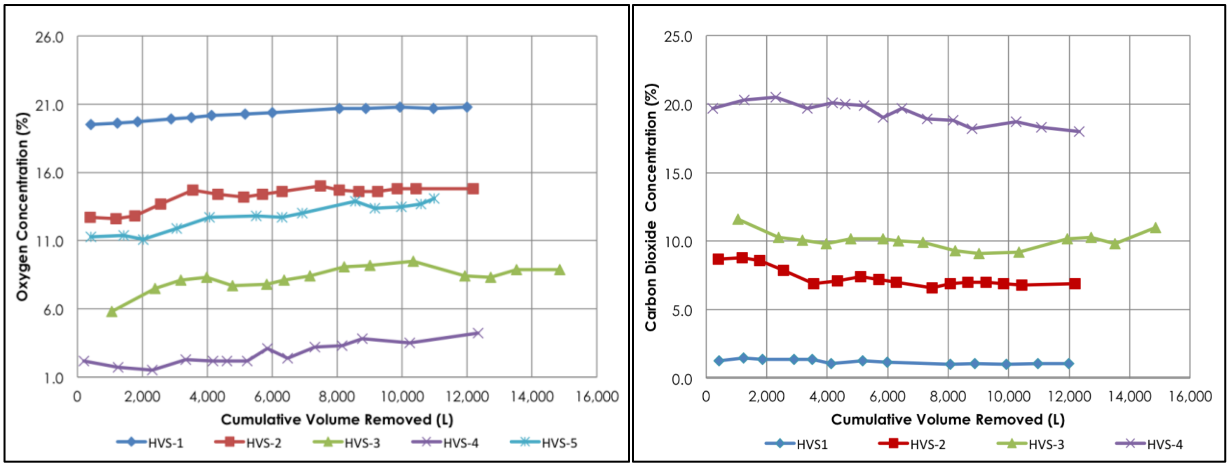

Figure 3: Example data for O_2 and CO_2 as a function of volume purged (McAlary, 2016)

Future Research

Research is ongoing regarding how to use the pneumatic testing analysis to optimize mitigation system design [ESTCP ER-201322], but in the interim, Equation 3 (in the Technical Appendix) provides useful information on the radial profile of vacuum. Many radon practitioners are expressing the opinion that mitigation systems can be effective with applied vacuums as low as 1 or 2 pascals, but that can be difficult to measure relative to baseline drift from wind gusts and other transient pressure effects, so a calibrated model of the vacuum profile would be very useful. Other potential metrics include the sub-slab ventilation rate and mass removal rate, which are both quantified by the HVS test data.

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Technical Appendix
Considerations for HVS Implementation

This section describes the HVS test equipment, design, testing components and example data. Several types of data are collected, each serving a specific purpose as tabulated below (Table 1):

Table 1. Summary of HVS Testing Parameters

Parameter	Testing Procedure	Rationale
VOC vapor concentrations	Field screening (PID or FID) as a function of volume purged, plus selected grab samples for laboratory analysis	Indicates volume-average VOC vapor concentrations and VOC vapor distribution at progressively farther distances from sampling point.
Permeability of sub-floor material	Transient and steady-state flow and vacuum measurements	Provides data to support mathematical modeling and venting system design (if needed).
Leakance of floor slab	O_2/CO_2 tracer tests and Hantush-Jacob Model analysis of transient and steady vacuum response data	Provides data to quantify amount of dilution attributable to leakage of indoor air across the floor, and provides a basis for mass balance calculations to calculate sub-slab vapor concentrations prior to dilution.
Velocity of gas flow below floor	Helium tracer tests (inter-probe and/or flood)	Verifies the distance from which gas was drawn during the test, and radius of influence for mitigation (if needed).
Predictions between and beyond sampling locations	Spreadsheet analysis using equations for vacuum, velocity and leakage versus radial distance	Verify internal consistency between field data and model assumptions, support the conceptual model, and potentially identify the presence of preferential pathways.

1) Equipment Testing

The equipment for HVS testing (as shown in Figure 1) must be checked for leaks to ensure accurate test results. The seal of the pipe to the cored hole can be verified using a water dam. A water dam is a cylinder secured to the floor using plumber's putty or similar gasket, which surrounds the penetration through the floor. An inch of water is added to the water dam, and if the water level inside the dam is steady during the HVS test, the seal between the extraction pipe and the concrete floor must be competent. A shut-in test can also be used to verify the absence of leaks in the apparatus, or the apparatus can be pressurized and the fittings can be sprayed with a soapy water solution to assess whether air-bubbles form at the fitting prior to testing. A bleed air valve is included downstream of the flow and vacuum measurements and sample collection ports to allow some bleed air to keep the fan from overheating if the flow rate of extracted gas is low. After the test is complete, the cored hole and all communication test points must be sealed with a durable, air-tight seal (e.g., fast-setting anchor cement).

2) Approximate Radius of Gas Extraction

A simple way to estimate the radius from which the gas is extracted is to use the volume of a cylinder:

$$V = \pi r^2 bn \qquad \text{Eqn. 1}$$

where:

V = the volume of gas extracted (flow rate times the time since the start of the test),

π = 3.14159

r = radius from which gas is withdrawn,

b = thickness of the sub-slab interval through which gas flows (this is often the thickness of the granular fill below the floor slab, but can be thinner if there is a dessication gap below the floor or thicker if the native soil has a permeability similar to or greater than construction aggregate), and

n = effective gas-filled porosity.

For example, if an HVS test is run at 50 scfm and there is a 6-inch granular fill layer below the slab with an air-filled porosity of 30%, the average radius from which gas would be extracted over time would be as shown in Figure 4. Actual flow conditions will vary with site-specific variations in the permeability and thickness of materials below the slab, so this is an approximation. The radius of influence expands until the amount of air leaking across the floor slab equals the amount of air extracted at the suction point. Leakage is therefore quantified, as described below.

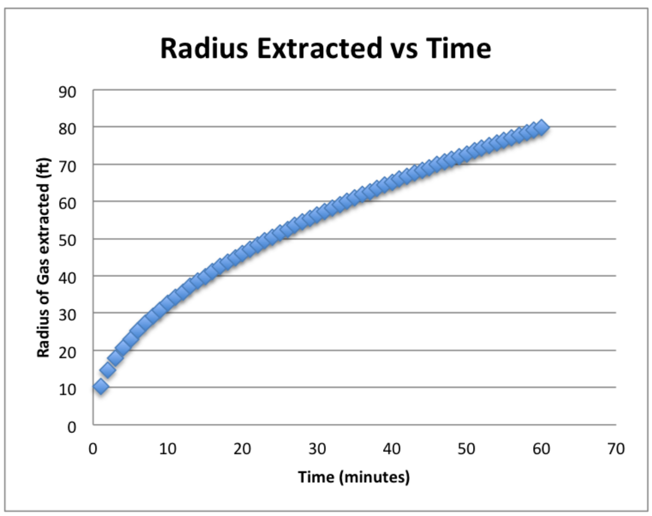

Figure 4: Approximate radius from which gas would be extracted as a function of time during an HVS test at 50 scfm (with a 6-inch gravel layer of 30% porosity below a competent slab) (Courtesy of Geosyntec)

3) Transmissivity of Sub-slab Materials

The transmissivity of the material below the floor dictates the sustainable flow rate, although the flow rate can be improved somewhat by removing some soil from below the slab to make a suction pit, similar to conventional radon system vent-pipe design. Fortunately, most concrete floor slabs are placed on top of compacted granular fill, which is highly permeable because this is specified in building codes (e.g., Figures R403.1(2), R403(3).3 and Section 403.2 of the California Residential Code and 1805.4.1 of the California Building Code).

Sometimes, the material below the floor is native soil, which can have a wide range of texture and permeability. Most soils are far more permeable than concrete, even fractured concrete, so the path of least resistance during an HVS test is through the soil. The HVS test is not effective in cases where the flow during the high volume test is very low (e.g., less than about 1 scfm) at a very high vacuum (e.g., more than 40 inches of water column). However, clayey soils often desiccate and shrink, causing a gap below the floor, so the HVS method can draw gas from considerable distances, even if the material below the gap is not very permeable.

4) VOC and Fixed Gas Concentrations as a Function of Volume Purged

A vacuum chamber (a.k.a., "lung box") can be used to draw gas samples into a Tedlar® bag from the sampling port at the suction point. Periodic samples (every 5 minutes or so) will usually be sufficient to document the trends in VOC and $O_2/CO_2/CH_4$ concentrations. The sample port should be fitted with gas-tight valves and inert tubing to facilitate sampling and minimize the risk of bias from sorption and leakage.

A grab sample for laboratory analysis can be collected at the suction point (i.e., upstream of the dilution air valve) at the beginning of each HVS test after a steady flow from the apparatus is established. A second sample can be collected at the end if there is an indication of changes in the total VOC readings via PID or FID.

5) Tracer Testing

Two types of sub-slab tracer testing can be performed to verify the travel time for gas migration below the slab during the HVS test. The tracer test data can be used to verify the distances from which gas was extracted during the HVS test, using the calculations in this Technical Appendix. Inter-probe tracer tests are conducted by injecting a certain volume of gas (e.g., 10 L of helium) into a sub-slab probe at a certain distance (e.g., 5 to 15 feet) from the suction point, and monitoring the concentration of the tracer in the gas extracted over time. The time between the midpoint of the injection and the maximum concentration in the extracted gas is the travel time for gas below the floor from the point of injection to the point of suction.

A tracer flood may also be conducted by reversing the direction of flow (blowing air into the subsurface), and adding tracer to the injected air (e.g., 1 % helium). Monitoring is conducted at sub-slab probes at various radial distances from the injection point. The average travel time is the time required for the tracer concentration in the probe to reach 50% of the injected concentration.

6) Steady-State and Transient Vacuum Response Testing and Analysis

Steady-state vacuum response data (vacuum versus distance) are measured in sub-slab probes (sometimes referred to as communication test points in the radon literature). Ideally, there should be at least one point in relatively close proximity to the point of suction (e.g., 3 feet or 1 m away), and at least one point farther away (e.g., 30 feet or 10 m). Vacuum usually stabilizes within minutes, and can be measured any time after.

Transient vacuum response data (vacuum versus time) are analogous to measuring drawdown versus time at a piezometer during a groundwater pumping test, and can be analyzed using the semi-confined (leaky) aquifer model (Hantush and Jacob, 1955). A correction is needed for different densities and viscosities of water and air (Thrupp et al., 1996); otherwise the governing equations for flow through porous media are identical for gas and water (Bear, 1979). Both transient and steady-state vacuum response data are used to calculate the transmissivity of material below the floor and leakance of the floor, as described below, which provides the parameter values needed to calculate profiles or vacuum, velocity, travel time and leakance as a function of radial distance from the suction point.

The conceptual model developed by Hantush and Jacob (1955) (Figure 5) is analogous for the HVS test where the leaky aquitard (or semi-pervious layer) is the floor slab and the aquifer is the soil or granular fill below the floor slab.

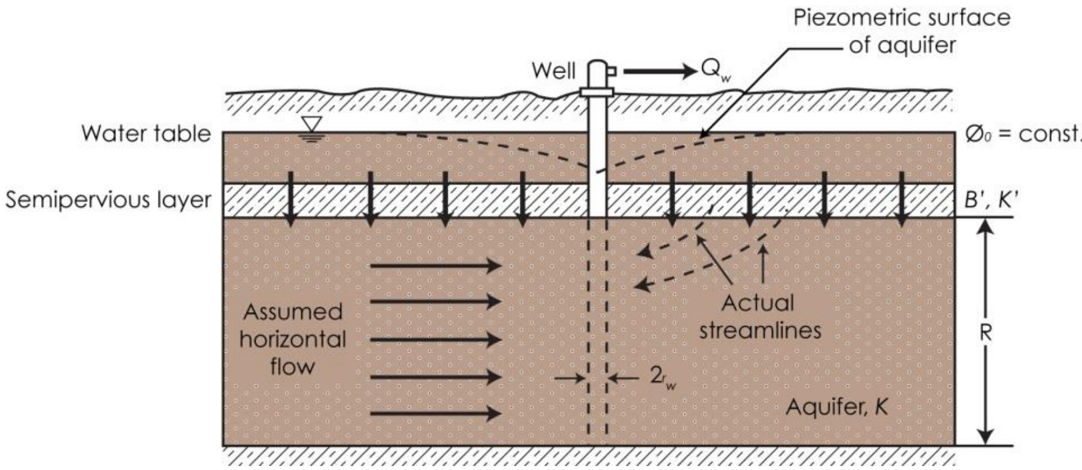

Figure 5: Conceptual Model for the Hantush-Jacob (1955) Leaky Aquifer Solution (McAlary et al., 2010)

The transient vacuum response to sub-slab gas extraction is usually very fast (see Figure 6), and two or more sets of data can typically be collected by turning the fan on and off repeatedly over the course of a few minutes, which allows comparison between the responses to check for consistency. The transient pneumatic testing is best performed at the end of the HVS test, after the field screening and laboratory samples have been collected for analysis, so as not to bias the vapor and fixed gas concentrations. Pressure transducers with data loggers are required to capture the transient vacuum response data.

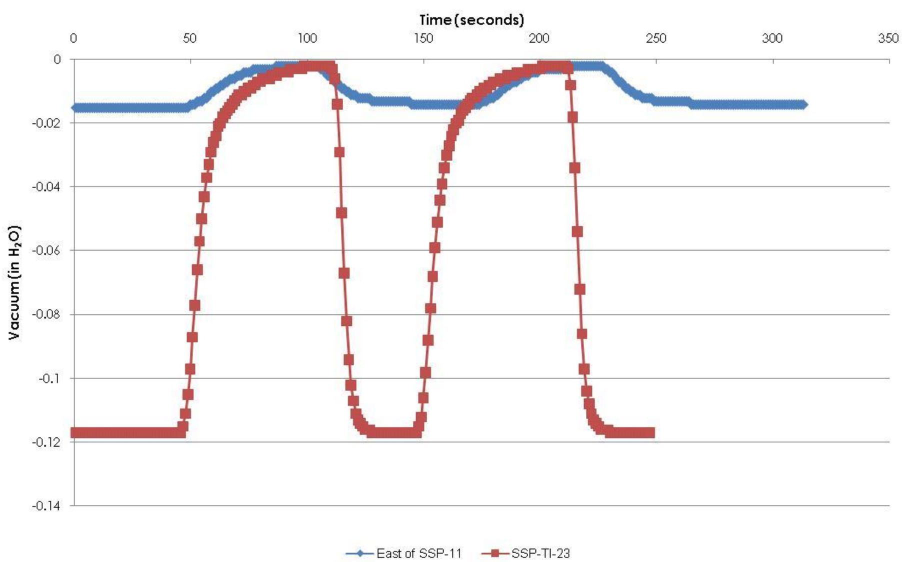

Figure 6: Typical transient vacuum response to cyclic pumping, showing two cycles of drawdown and recovery from two monitoring probes at different radial distances (McAlary et al., 2010).

i) Transmissivity and Leakance

Fitting the Hantush-Jacob model to the transient vacuum response data (Figure 7) provides the transmissivity (T) of gas flow through materials beneath the floor slab and the vertical leakance (B) of air flow into the subsurface (i.e., across the slab). The leakage factor (B) is defined as follows:

$$B = \sqrt{\frac{Tb'}{K'}} \qquad \text{Eqn. 2}$$

where:

T = Transmissivity of the zone of extraction [L^2/T],

b' = Thickness of the semi-confining zone [L], and

K´ = Vertical pneumatic conductivity of semi-confining zone [L/T].

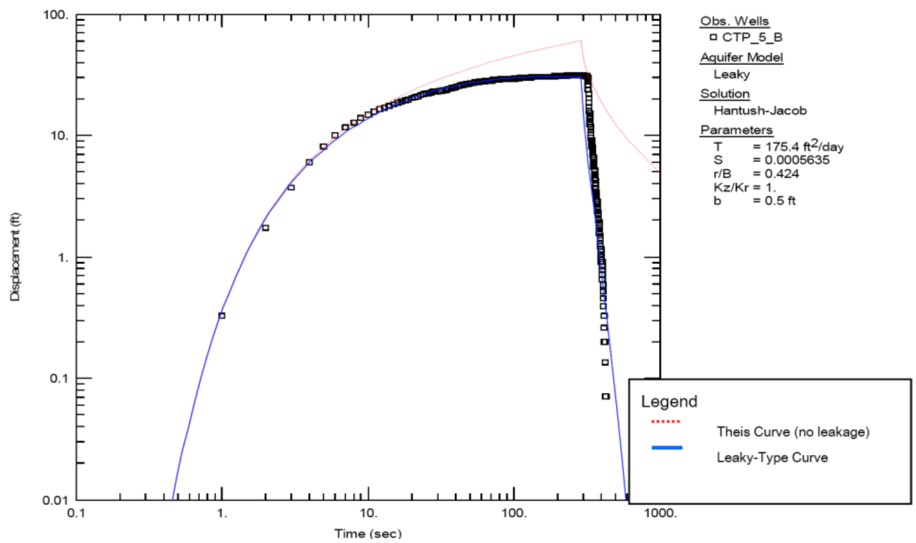

Figure 7: Example of mathematical model fitting to the transient vacuum response data (McAlary et al., 2011)

The fit between the measured transient vacuum data (squares) and Hantush-Jacob Model (line) on Figure 7 is excellent during both drawdown and recovery, which is observed in most cases, and indicates that the gas flow occurs in a manner consistent with the assumptions in the formulation of the model (uniform, homogenous, isotropic, semi-infinite domain). Where the data do not fit the model, this provides an indication of the presence of irregularities such as atypical preferential pathways below the floor (which are otherwise difficult to identify).

ii) Mathematical Modeling

Once the T and B values have been determined, several relationships can be modeled using simple equations that can be programmed into a spreadsheet:

a) **vacuum versus distance**

$$S(r) = \frac{Q_W}{2\pi T} K_o(r/B)$$

Eqn. 3

where:

B = leakage factor as defined above and:

S(r) = vacuum in units of air column [F/L^2],

r = radial distance from extraction point [L],

Q_W = discharge from the extraction point [L^3/T],

T = transmissivity of the zone of extraction [L^2/T], and

K_o = Modified Bessel Function of zero order of r/B [dimensionless].

The calculated profile of vacuum versus distance should be compared to the steady-state vacuum profile measured near the end of the HVS test using sub-slab probes at various distances from the point(s) of suction. The T and B values may need to be adjusted iteratively to achieve values that provide the best match to both the transient (time-drawdown) and steady-state (distance-drawdown) data sets. This analysis involves two variables (T and B) and two independent sets of data, so a unique solution is typically obtained, providing the subsurface conditions are a reasonable match to the Hantush-Jacob model assumptions and the suction point is far from boundaries such as exterior walls of the building. Locations with measured steady vacuum levels that are different than the values calculated with Equation 3 provide clues regarding atypical preferential pathways (where the measured vacuum is low, gas must be able to flow more readily to the region of the measurement).

b) travel time to the point of suction versus distance

Sub-slab gas velocity can be calculated using:

$$v(r) = \frac{Q_W}{2\pi b n} \frac{1}{B} K_1(r/B)$$

Eqn. 4

where Q_w, B and r are as defined above and:

v(r) = velocity at a specific radial distance (r) from the extraction point [L],

b = thickness of permeable layer below the floor [L],

n = air-filled porosity of the material below the floor [L^3/L^3], and

K_1 = modified Bessel function of first order of r/B [dimensionless].

Travel time (t_{travel}) from a given distance can be determined by integrating the velocities over discrete segments of the distance using:

$$t_{travel} = \int \frac{\partial r}{v(r)}$$

Eqn. 5

The air-filled porosity of the material below the floor is expected to be similar to the total porosity because the building prevents infiltration of precipitation, so the materials below the floor usually drain to field capacity. Porosity of soils is generally in the range of 0.25 to 0.4, which is a relatively narrow range, so this parameter is not particularly sensitive. The thickness of the permeable layer can vary over a broader range and therefore can have a more significant effect on the calculated flow velocity below the floor. The tracer tests (inter-probe or flood) provide an independent line of evidence for comparison to the calculated velocity, which provides calibration of the T and r/B values and verification of the b value (thickness of the permeable layer).

c) **the percentage of total gas withdrawn compared to the amount of air leaking across the slab as a function of distance**

Equation 6 can be used to calculate the ventilation rate below the floor as a function of the radial distance from the suction points, which is a valuable tool for calculating the degree of dilution affecting the HVS samples for laboratory analysis and selecting the necessary and sufficient number of suction points for a mitigation system.

$$Q(r)/Qw = \frac{r}{B} K_1(r/B) \qquad \text{Eqn. 6}$$

where r, B, and Q_W are as defined above and:

Q(r) = flow originating in the subsurface from a distance r away from the suction point [L^3/T], and

K_1 = Modified Bessel Function of the second kind of order one of (r/B) [dimensionless].

Figure 8 shows the proportion of flow from the subsurface (Q_{ss}) as a percentage of the total flow from the well (Q_w) as a function of the radial distance from the point of suction.

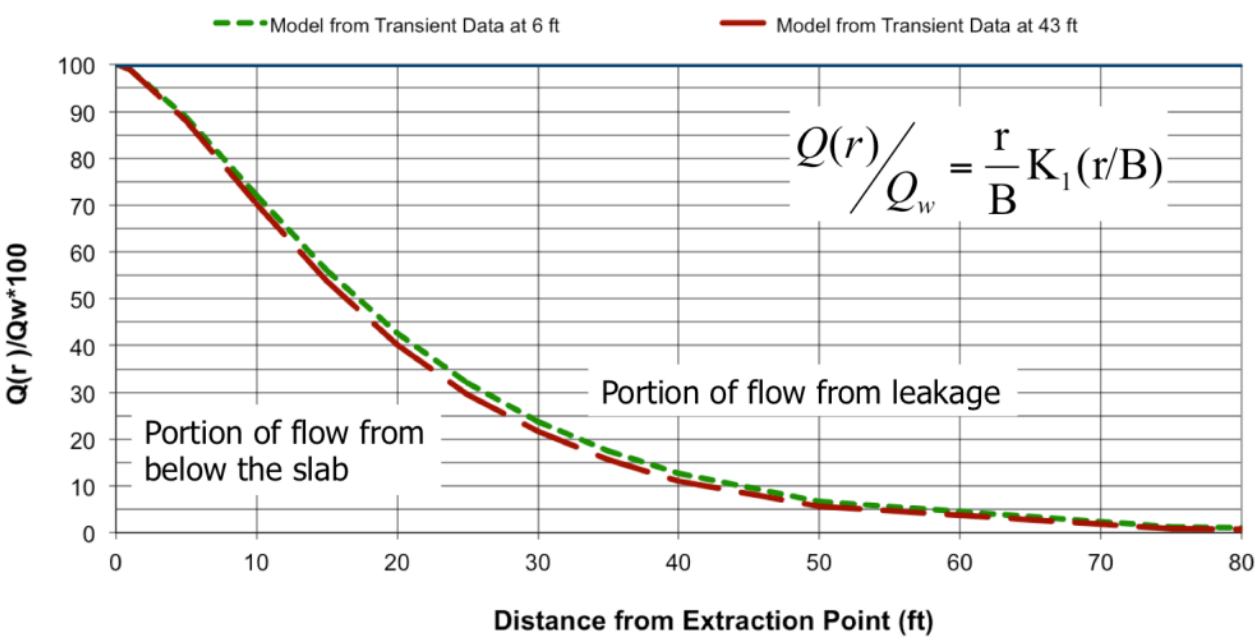

Figure 8: Relative proportions of flow from above and below the floor as a function of distance from the suction point (McAlary et al., 2011)

d) **building-specific attenuation factor**

Equation 2 can be rearranged to solve for the bulk average gas conductivity of the floor slab (K'). The flow rate of soil gas into the building (Q_{soil}) per unit area can also be calculated if the pressure differential across the floor slab (ΔP) is also measured under ambient conditions.

$$Q_{soil} = K' (\Delta P/b') \qquad \text{Eqn. 7}$$

A building-specific attenuation factor (α) can then be calculated by dividing Q_{soil} by the volumetric flow of air through the occupied building space (Q_{build}) per unit area, which is simply the height of the lowest floor (h) multiplied by the air exchange rate (AER). This information may be available from a heating, ventilation, and air conditioning (HVAC) engineer or estimated from literature values for a particular building type (e.g., EPA, 2011 lists the mean air exchange per hour as 0.6 for commercial buildings, with a range of 0.3 to 4.1).

$$\text{Building-Specific } \alpha = \frac{K' (\Delta P/b')}{h \text{ AER}} \qquad \text{Eqn. 8}$$

For example, if the calculated T value is 250 ft^2/day, B is 15 ft, and the slab thickness (b') is 0.5 ft, then K' will be 0.5 ft/day via Equation 2. If the average differential pressure across the floor slab is 0.001 inches of water column (roughly 0.09 ft of air column), the average ceiling height (h) is 20 ft and the average air exchange rate is about 14 per day, the building-specific attenuation factor (α) would be 0.0003 via Equation 8. This is typical for many commercial buildings. The indoor air risk-based screening level can be divided by the building-specific attenuation factor to calculate sub-slab screening levels. Also, the sub-slab concentrations can be multiplied by the building-specific attenuation factor to calculate the expected indoor air concentration for assessing potential risks and identifying measured indoor air concentrations that are likely to be biased by background sources.