MassDEP

FIELD ASSESSMENT AND SUPPORT TEAM (FAST)

An Expedited Approach to the Investigation and Mitigation of the Vapor Intrusion Pathway

OBSERVATIONS, FINDINGS & RECOMMENDATIONS

West Street Area

Newton, MA

October 2016

Table of Contents

Table of Tables

Table of Figures

EXECUTIVE SUMMARY/FINDINGS

A series of innovative steps and procedures were undertaken during the investigation and mitigation of (TCE) vapor intrusion pathways in a neighborhood in Newton, MA, in order to accelerate the pace of assessment, decrease costs, and optimize remedial outcomes. Key observations and finding in this regard are summarized below:

1. Low-cost direct-push wells were found to be an expedient and cost-effective means to obtain groundwater samples at the water table interface, provided subsurface conditions are appropriate (i.e., minimal rocks/cobbles).

2. On-site groundwater testing using a gas chromatographic headspace screening procedure was found to provide quantification data for common VOCs (e.g., TCE) similar (+/- 30%) to values obtained using the EPA Method 8260 purge-and-trap testing procedure, except at very high concentration levels (> 10,000 mg/L).

3. The collection of indoor air samples using 0.5 to 1-Liter bags was found to be an imperfect but adequate means to obtain samples for the determination of "Imminent Hazard" levels of VOC contaminants, including TCE.
    a. Bags made of polyvinylidene fluoride (PVDF) resin, marketed as Kynar®, appear to have the least amount of problematic manufacturing impurities, compared to other commercially available products (e.g., Tedlar®).
    b. Based upon laboratory studies, sorptive losses upon filling appeared to be relatively minor (10 to 15%) for the Kynar® bags used for the Newton project.
    c. Based upon repeated analyses of actual indoor air samples, TCE losses in the Kynar bags were minor (< 10%) for up to a 48-hour holding time when concentration levels were less than 20 $\mu g/m^3$.
    d. Because of the variability among manufacturers, off-gassing and sorptive studies should be undertaken to quantify bias in the specific bags being used for indoor air analysis.

4. When properly calibrated and operated, the INFICON HAPSITE "portable" gas chromatograph/mass spectrometer (GC/MS) units were able to accurately identify and quantify TCE and other VOCs at concentrations as low as 1 $\mu g/m^3$ in a full-scan mode.

5. Two-minute "grab sample" data were found to be reasonably representative of indoor air conditions in structures or portions of structures where the short-term ($\leq$ 24 hour) air-exchange rate is relatively low, including typical basement spaces within residential dwellings. During this project, for basement samples, there was good agreement between 2-minute Kynar® bag samples and 24-hour passivated canister samples analyzed via EPA Method TO-15 ($r^2 = 0.9515$), especially when "high concentration" outliers (TCE > 100 $\mu g/m^3$) are excluded ($r^2 = 0.9992$). Variability was higher but still relatively good ($r^2= 0.9089$) for first floor samples.

6. The longer-term variability in TCE concentrations in a residential basement was found to be relatively modest. Daily grab samples obtained from an impacted basement space over a 2 week period identified levels of TCE in the range of 9 to 18 $\mu g/m^3$; much less than the "order of magnitude" variation reported by some researchers. Such data were obtained during winter conditions (late February to early March) in a basement space with a natural-vent combustion boiler and water heater, in which the outdoor

temperature varied from 0^{o} to 45^{o}F, barometric pressure ranged from 29.67 to 30.74 inches of mercury, and wind speeds ranged from 4 to 26 MPH.

7. As reported by many researchers, the vapor intrusion pathway was found to be complex and highly variable; data from 1 to 4 sub-slab soil vapor probes and close-by structures were not sufficient to rule out a pathway of concern in any given building. Indoor air testing, particularly in the basement level, was needed to make reasonable conclusions in this regard.

8. While the use of Air-Purifying Units (APUs) containing activated carbon can be an important and effective initial mitigation measure, uncertainties exist over the extent and rate of sorption at the low concentration levels of concern (i.e., 5 to 100 μg/m^3).
    a. Isotherm and design guidance for activated carbon filters are generally based upon experimentation conducted at 100 ppmV; 4 to 5 orders of magnitude higher than levels of concern at vapor intrusion sites.
    b. At low μg/m^3 levels, the sorption of VOCs appears to be controlled by the diffusive flux of contaminants through macropores and into micropores within the activated carbon media. As such, the rate of sorption/removal of VOCs within indoor air declines exponentially as concentrations within indoor air drop below 25 to 50 μg/m^3.
    c. At the Newton site, in a typical basement or first floor space of 3500 to 5500 ft^3, an APU containing 12.5 pounds of granular activated carbon required about 1 week to reduce high concentrations of TCE (> 50 μg/m^3) within indoor air by a factor of 50%; and about two weeks to reduce lower concentrations of TCE (< 20 μg/m^3) within indoor air by a factor of 50%. Even after over 10 weeks of operation, a single APU was not capable of reducing high levels of TCE (> 50 μg/m^3) to less than 6 μg/m^3 , the Imminent Hazard concentration within a residential setting with sensitive receptors (i.e., women of child-bearing age).
    d. Multiple APUs (or APUs with larger amounts of activated carbon) may be needed to achieve initial mitigation goals (e.g., < 6 μg/m^3) within a 1 to 2 week timeframe, particularly where TCE indoor air concentrations exceed 50 μg/m^3, or where Relative Humidity is > 50% and/or high "background" concentrations of common indoor air contaminants (e.g., acetone, ethyl acetate) are present.

9. Sub-slab Depressurization (SSD) systems were found to be an effective means to reduce TCE concentrations within impacted spaces, generally to less than 1 μg/m^3.

10. Sub-slab diagnostic/communication testing, in a manner recommended by EPA and other radon-mitigation guidance documents, was found to be a reasonable and prudent step to optimize the design of SSD systems and selection of the extraction fans. At the Newton site, TCE was reduced to less than 1 μg/m^3 within 3 to 4 weeks in all homes except one; the exception being a basement apartment where only a single extraction leg was approved by the building owner, which was unable to propagate a negative pressure field under all areas of the basement slab. Even in this basement apartment, however, TCE concentrations were reduced to less than 3 μg/m^3.

BACKGROUND

As part of an audit of a Downgradient Property Status (DPS) report submitted to MassDEP, staff noted the presence of elevated concentrations of Trichloroethylene (TCE) in groundwater at a former auto-salvage parts facility on West Street in Newton. Existing wells at the site were sampled and analyzed by agency staff, confirming the presence of high levels of TCE at the water table interface in the densely populated residential neighborhood.

Anticipating a significant regional vapor-intrusion situation, and lacking a viable Responsible Party to fund investigations, a decision was made to forego a conventional state-funded contractor effort in an attempt to undertake needed work in a more timely and cost-effective manner. Investigative tools and protocols were explicitly "screening level", under the premise that such an approach was consistent with Data Quality Objectives and adequate to make decisions on the existence and elimination of Imminent Hazard conditions.

Accordingly, between September 2014 and May 2015, MassDEP FAST staff installed, sampled, and analyzed 39 groundwater monitoring wells, and obtained and analyzed 157 "grab" indoor air samples from 57 residential dwellings. Following this 9 month period of intensive site investigative work, additional wells were installed and additional indoor air samples were obtained to better define and confirm the extent of water-table contamination, and attempt to identify additional sources of area-wide contamination.

During the initial 9 month investigative period, TCE was detected (above 1 $\mu g/m^3$) in 19 of the sampled homes, exceeding Imminent Hazard concentrations in 7 dwellings. Air Purifying Units (APUs) were promptly installed in the homes with IH conditions to reduce TCE concentrations. In November of 2015, five Sub-slab Depressurization (SSD) Systems were installed by a state contractor in 4 different structures, using a fast-tracked bid process.

Complete details on the work completed at this site are provided in separate documents. The purpose of this report is to highlight significant observations, findings, and recommendations arising from the chosen approach, with respect to:

- The installation, use, and sampling of low-cost/direct-push groundwater monitoring wells
- Headspace screening of groundwater samples
- Temporal and spatial variability in sub-slab soil gas concentrations
- Utility of "grab" indoor air screening data
- The effectiveness of Air Purifying Units (APUs)
- The design, installation, and operational effectiveness of SSD systems

DIRECT-PUSH WELLS

Between September 23, 2014 and May 29, 2015, MassDEP/FAST installed 39 small-diameter direct-push wells, using an adaptive field sampling approach where investigative efforts are refined as new information and sampling data (including indoor air screening data) are obtained. A schematic and photos of these direct-push wells are provided in Figure 1.

Each well consists of 5-foot sections of common ¾-inch black pipe available at home centers. A local machine shop creates well screens by welding a conical tip and laser-cutting vertical slots into select 5 foot sections. The sections are connected via a 3-inch long steel coupling that is also fabricated at the machine shop.

The 5-foot well screen is initially driven into the ground using a hammer drill. A coupling is placed on the top of the well screen and a 5-foot solid riser pipe section is inserted into the other end of the coupling. The 5-foot riser section is then driven into the ground with the Hammer Drill. The process is repeated until the desired depth (or refusal) is achieved. A reciprocating saw is then use to cut off any part of the riser that extends above the ground surface, and a 1-½ PVC coupling and aluminum screw cap lid is used finish each well at grade.

Figure 1 – MassDEP/FAST Direct-Push Groundwater Monitoring Wells

Wells were advanced about 5 feet into groundwater, which was generally between 12 and 24 feet below grade. Most wells were installed on city property on the side of the roadway and on sidewalks, typically within 5 to 10 feet of a sanitary sewer.

GROUNDWATER HEADSPACE ANALYTICAL SCREENING

Water samples were obtained from each well using either an inertial or peristaltic pump. Each sample was then analyzed for TCE and other VOCs using a headspace screening procedure. In this approach, a 40-mL VOA vial is half-filled with the sample of interest. The vial is then hand-shaken for 15-seconds twice during a 10 to 15 minute headspace development period. An air-tight syringe is then used to pierce the vial septum and obtain a 1 to 4-mL sample of headspace gases. The headspace sample is immediately injected into a gas chromatograph; in this case, either an SRI GC/PID/ECLD unit or an INFICON HAPSITE GC/MS unit. The aqueous concentrations (µg/L) of VOC analytes are then calculated using Henry's Law, assuming a 75% equilibrium condition at 20^{o}C.

This screening technique has been used for approximately 20 years by agency scientists. Periodic comparison of split samples analyzed by the headspace screening technique and US EPA purge-and-trap method 8260 has typically shown good correlation. Such a comparison was made at the Newton site in August 2016 for 7 groundwater monitoring wells; the results are presented in Figure 2.

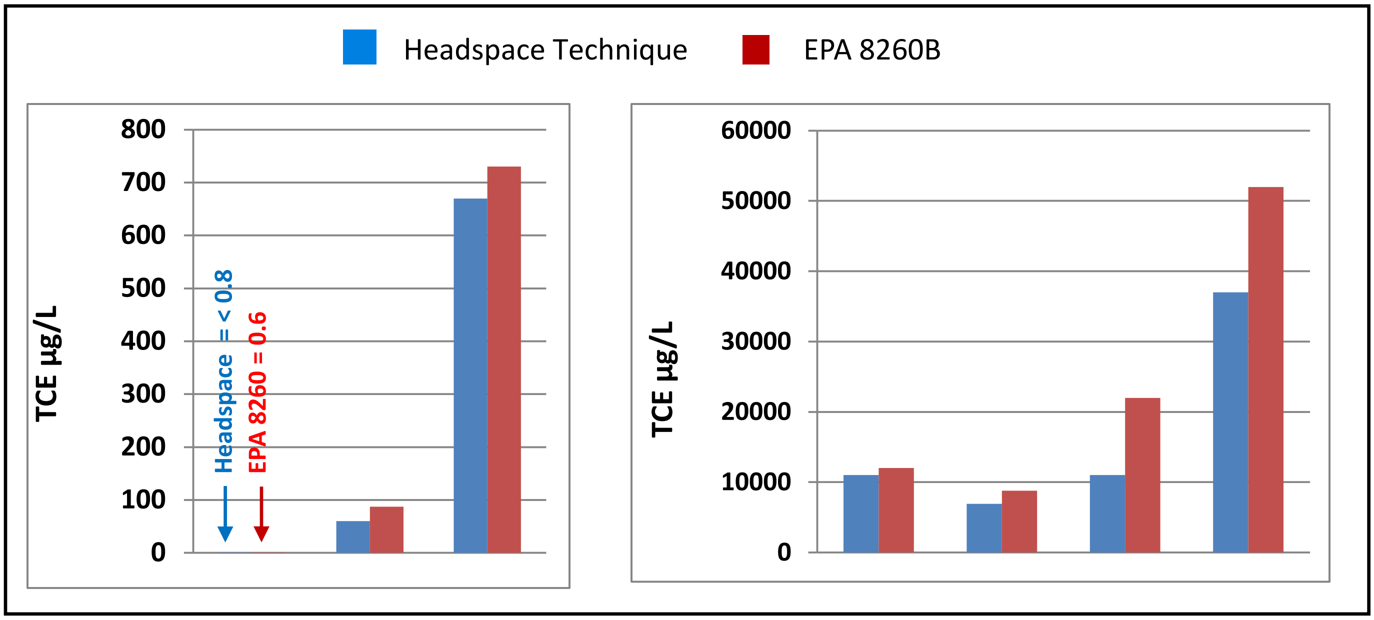


Figure 2 – Comparison of TCE Groundwater Data from 7 Monitoring Wells (August 2016)

Once again, the 15-minute headspace data is reasonably consistent with the EPA 8260B data, except for results in excess of 10,000 µg/L, where equilibrium conditions and partitioning kinetics lead to less reliable results. This is not deemed to be a significant limitation, as any concentrations of TCE above 10,000 µg/L is of great concern.

SUB-SLAB SOIL GAS

The investigation of sub-slab soil vapors are necessary to confirm the existence of a vapor intrusion pathway, and help construct a Conceptual Site Model. This involves both the installation of sub-slab soil vapor sampling probes, along with the use of a PID meter to screen cracks and void spaces.

All of the homes in Newton with Imminent Hazard vapor intrusion conditions were over 100 years old, with fieldstone and brick foundations, full basements, and concrete floor slabs of various thickness and integrity. Two of the structures housed duplex living units, one was a single-family home, and one was a former single family home converted into an apartment complex (including an apartment in the basement).

Groundwater was 5 to 10+ feet below the slab elevation at each location. All basements contained natural-draft (gas) combustion heating systems and water heaters.

Two to four soil vapor points were installed in each structure (see Figure 3). The underlying soil in all buildings appeared to be a mixture of cobbles, clay/silt, and ash.

Soil vapor samples were obtain in January and March, in 1-Liter Kynar bags, for analysis on a HAPSITE GC/MS. TCE data for key structures are presented in Figure 4

Figure 3 – Installing a Soil Gas Probe

As can be seen, there was significant spatial variability in TCE concentrations in probes. Temporal variability (between January and March) was less pronounced, but still significant.

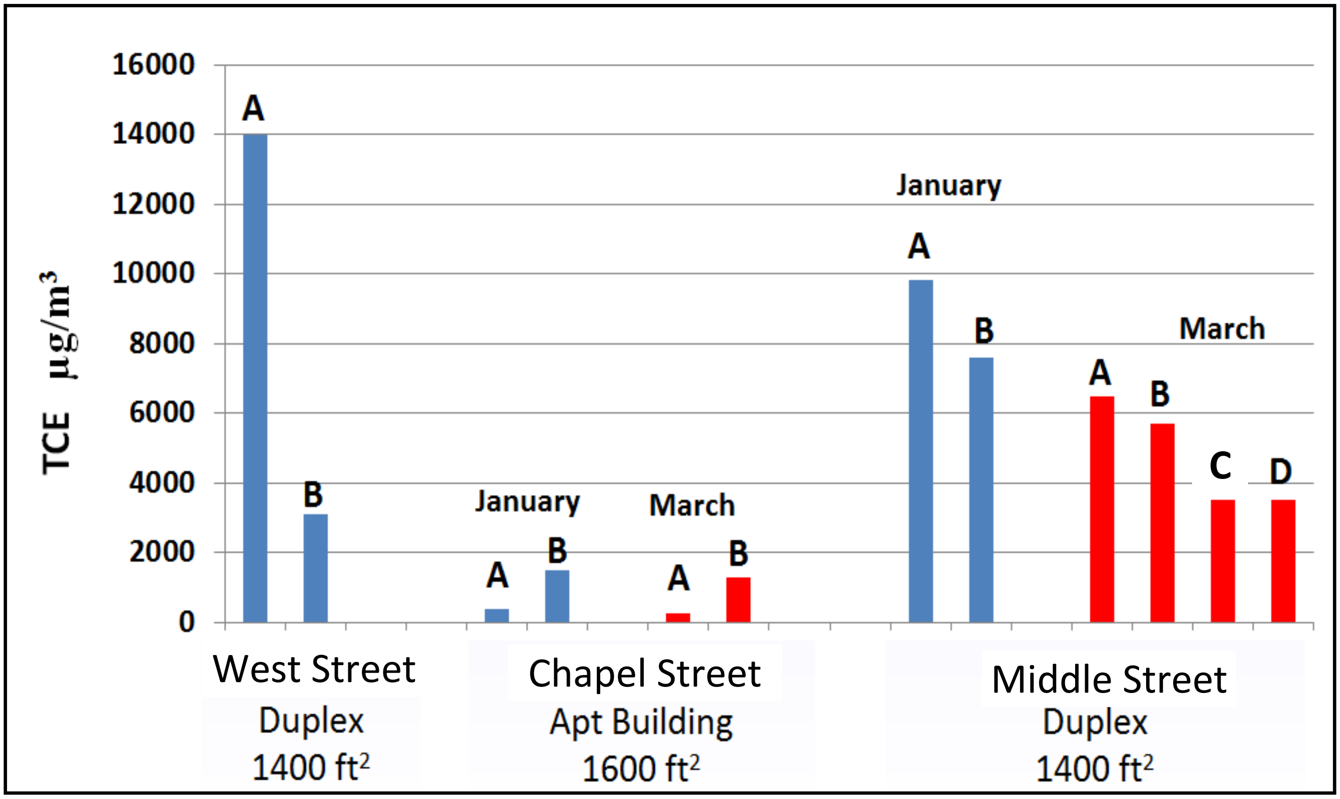


Figure 4 – Sub-Slab Soil Gas Concentrations of TCE (Grab Data)

To supplement soil vapor probe data, and further refine the Conceptual Site Model, a Photoionization Detector (PID) meter was used to screen cracks, void spaces, and floor drains in each home. Due to the presence of the ethene (double) bond, a PID is particularly sensitive to TCE, and is a low-cost, non-invasive tool to not only help confirm the existence of a vapor intrusion pathway, but also provide valuable insights on vapor intrusion mitigation.

While the PID meter used had a detection limit of 100 ppbV – well above indoor air concentrations of concern for TCE – it was more than adequate to detect discrete vapor entry points, where levels of TCE often exceeded 1 ppmV. Vapor entry typically occurs in such preferred flow pathways, which may collectively represent only a small percentage of the overall basement floor and wall envelope.

A positive PID response would be followed by the collection of a discrete air sample in a 1-Liter Kynar bag for follow-up analysis on a HAPSITE GC/MS unit. Using this approach, floor drains in one structure were confirmed to be a significant input point for TCE, while floor drains in another were not (i.e., no PID response and no significant GC/MS results). In an apartment building on Chapel Street, PID screening detected seeps of TCE vapors significantly higher than concentrations in nearby sub-slab soil vapor probes (see Figure 5).

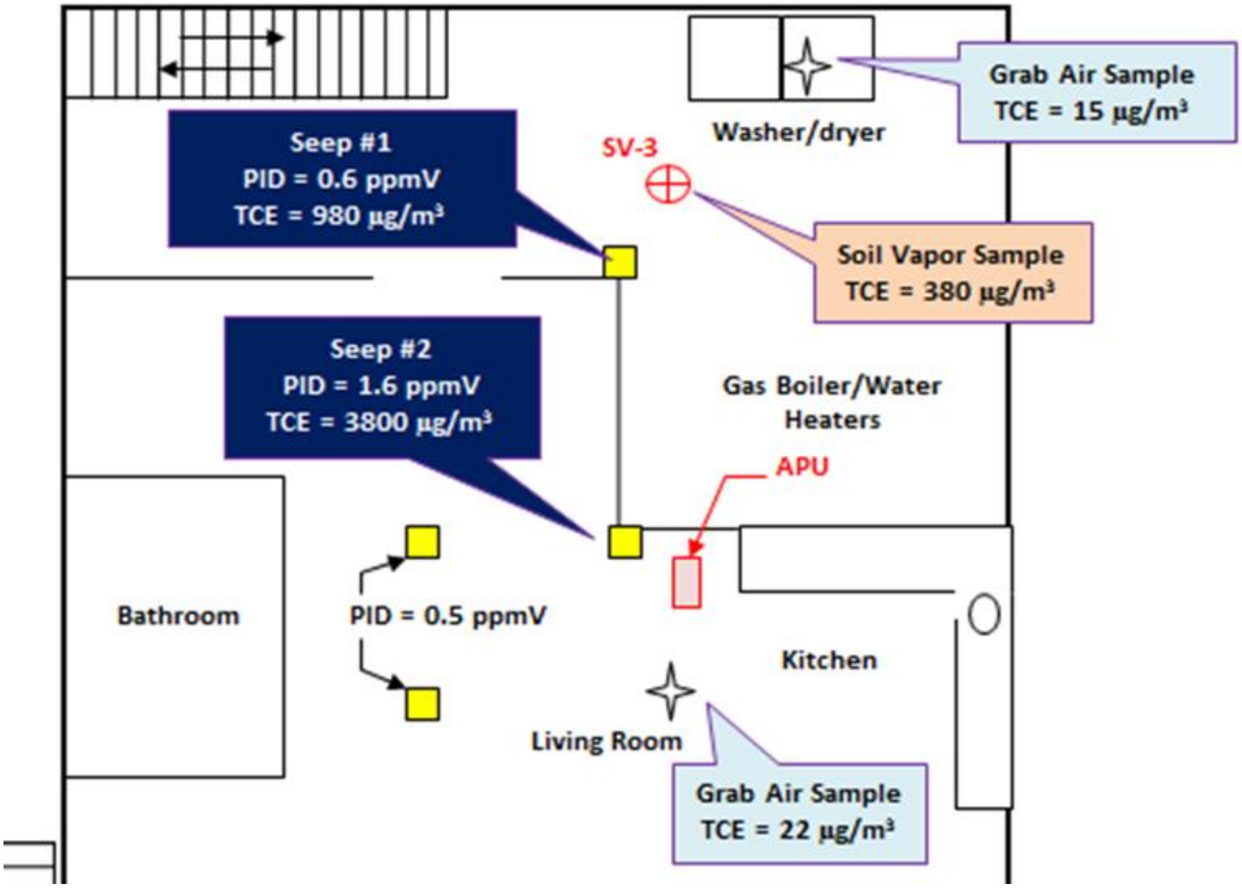


Figure 5 – PID Meter Screening in Basement Apartment on Chapel Street

In this case, seepage was occurring in the interface between structural columns and laminated flooring in a finished basement apartment. This finding was instrumental in mitigating risk in this structure, via the sealing of each seepage point with a low-VOC caulking material.

In November 2015, Sub-Slab Depressurization Systems (SSDS) were installed in those buildings with Imminent Hazard conditions. Vapor samples were obtained from the discharge of each system immediately after startup, under the premise that this "snapshot in time" best represented the true concentration of TCE present in the slab below each structure.

A comparison of these data to the average concentration of TCE in sub-slab soil vapor probes is provided in Figure 6 (note: the average concentration of TCE in the sub-slab probes was from data obtained in January and March 2015). The corresponding subslab-to-basement air Dilution Factors for each data set are provided in Figure 7.

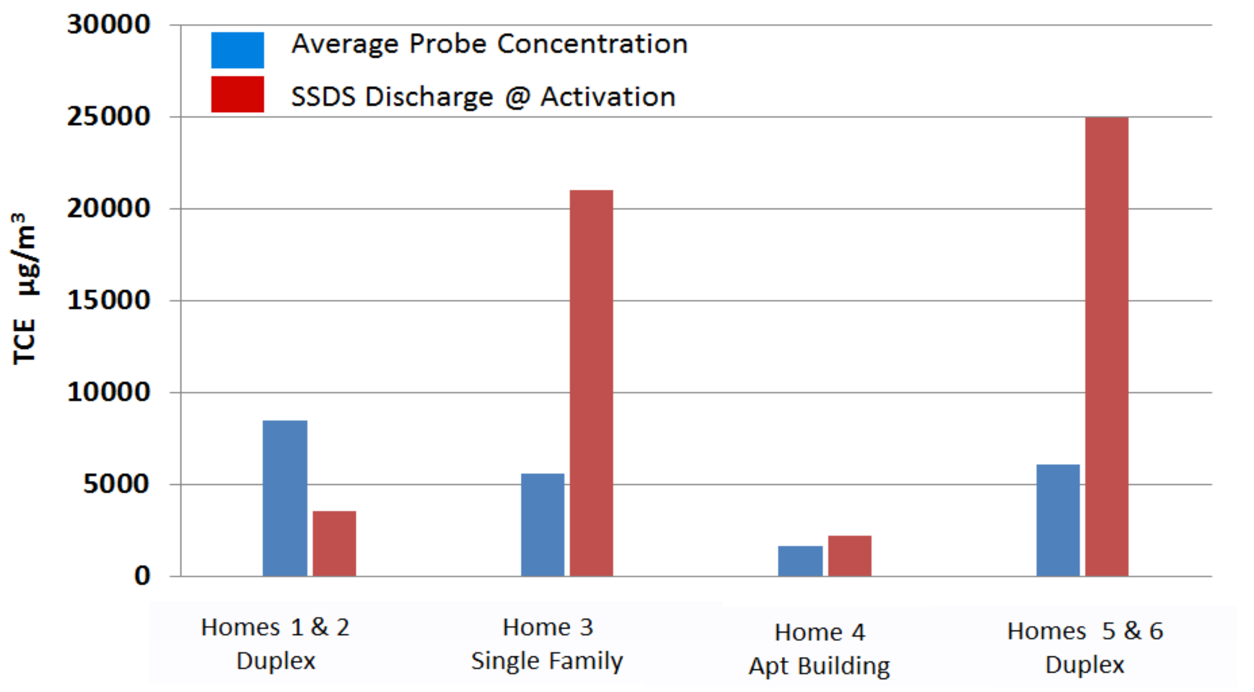


Figure 6 – TCE Concentrations in Sub-Slab Vapor Points vs. SSDS influent

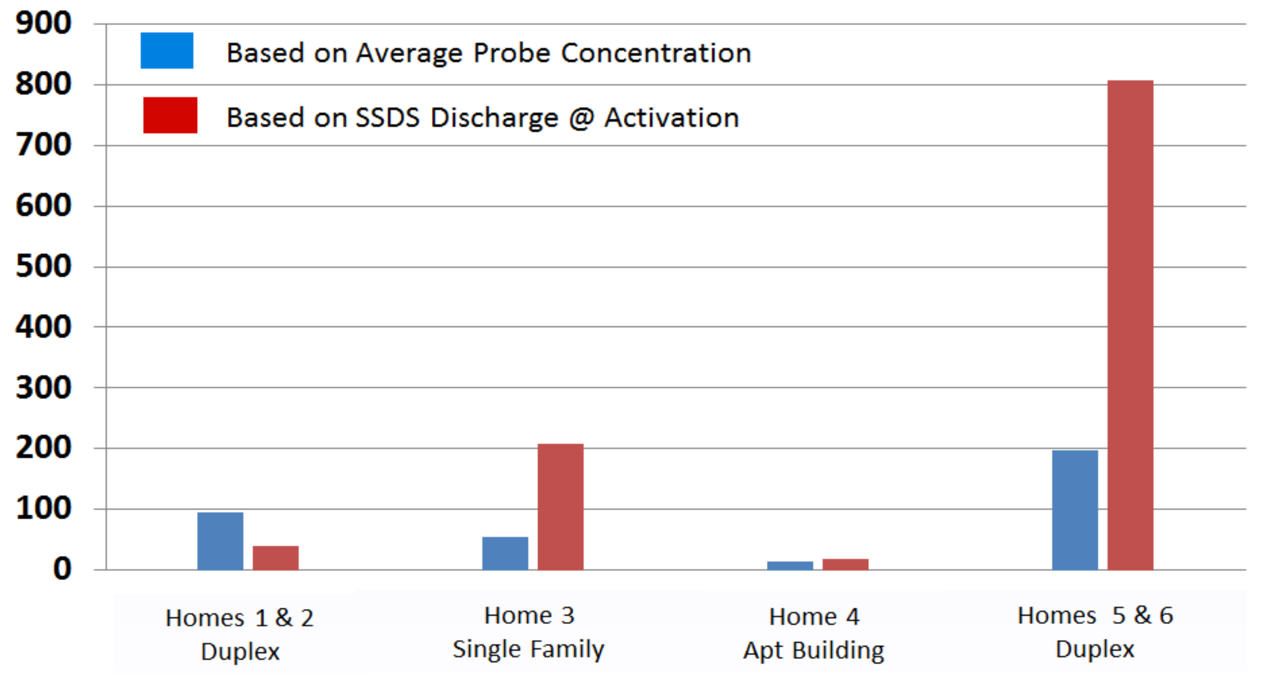


Figure 7 – Sub-Slab/Basement-Air Dilution Factors

As can be seen, there was significant variability between sub-slab probe data and SSDS discharge data. This is not unexpected, given the substantial spatial variability in sub-slab vapor concentrations that have been reported by numerous researchers. In some cases, the use of sub-slab probes can overstate vapor concentration, in others, understate. This leads to a wide variability in Dilution Factors, as shown in Figure 7, verifying a "rule of thumb" metric of a 10 to 1000-fold range Dilution Factor.

Pathway Variability

Observations and data on Dilution/Attenuation Factors from the Newton study illustrate the significant variability in structure vulnerability to the vapor intrusion pathway. Figure 8 details two examples of where contiguous buildings, only 10 to 15 feet apart, had very different conditions (i.e., impact vs. no or no significant impact).

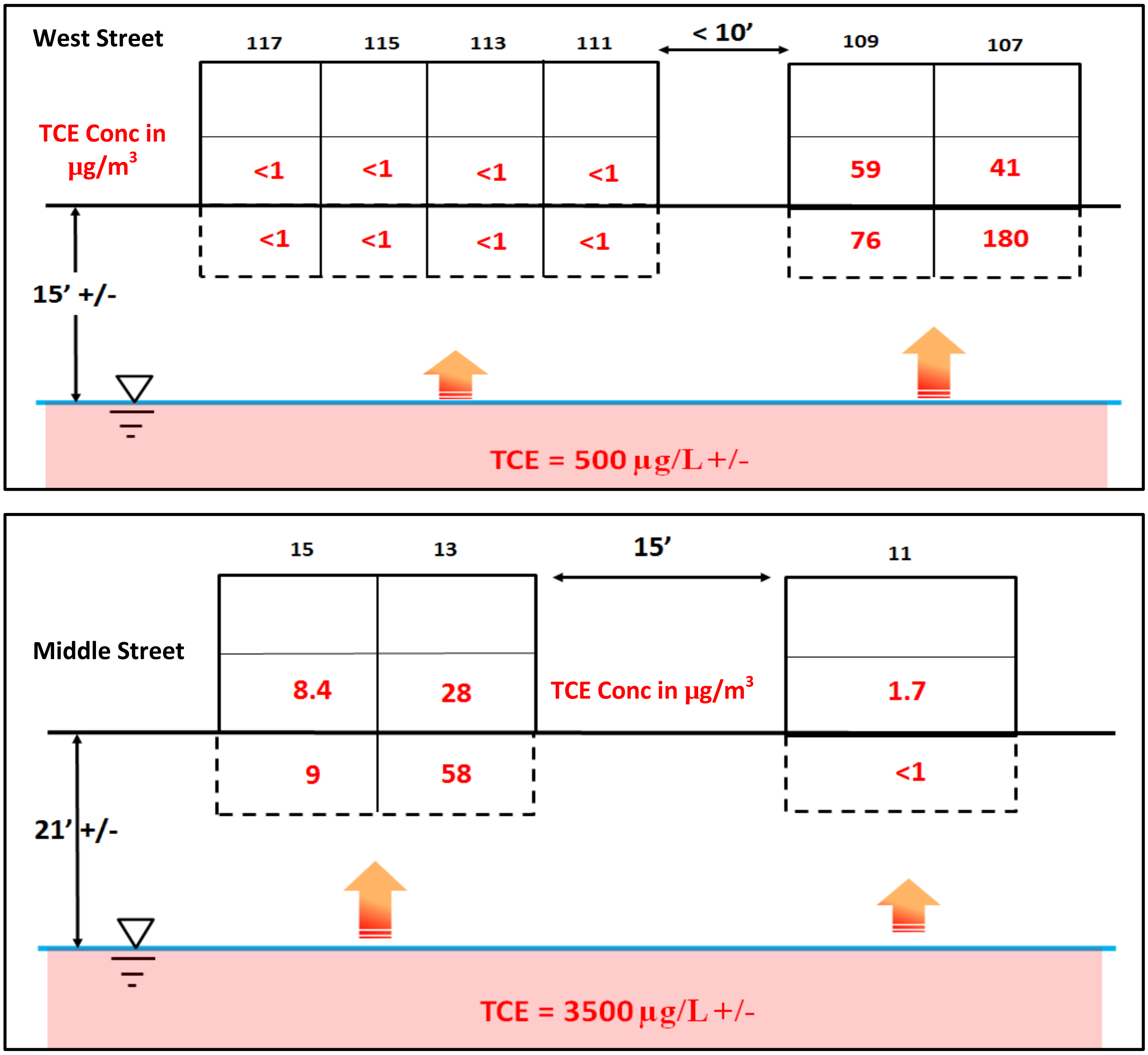


Figure 8 – Vapor Intrusion Conditions in Contiguous Structures

This variability speaks to the heterogeneities in sub-surface conditions and the existence or absence of vapor migration pathways (e.g., pipes/conduits, voids, soil macro-pores), along with building parameters such as depressurization conditions and ventilation rates. It should be noted that no obvious vapor entry points were identified in the impacted structures depicted in Figure 8 (i.e., both had reasonably intact concrete floor slabs with no floor drain vapor migration conduits).

Also noteworthy was the depth to groundwater in both locations, which affirms that a vapor intrusion pathway is possible even if depth to groundwater is greater than 15 feet (at least if VOC concentrations in groundwater are highly elevated).

USE AND UTILITY OF FAST “GRAB” INDOOR AIR DATA

FAST assets include two INFICON HAPSITE gas chromatographs/mass spectrometers (GC/MS). Both units are mobile and can be used either in a laboratory space at MassDEP or in a mobile laboratory (see Figure 9).

“ER” (blue) and “SP” (yellow) units in Mobile Laboratory

Close up of sampling probes and 1-Liter Kynar bags

Figure 9 – HAPSITE GC/MS units

Instruments and Methods

Both of the HAPSITE GC/MS units contain a 30-meter capillary column (0.32 mm ID x 1µ film). Only gaseous samples may be introduced into the units, via hand probes (with heated transfer lines) that sample at about 113 cc/min. During each run, 2 internal standards contained in a cylinder within the units are automatically injected into the sample stream. An activated-carbon “tri-bed” concentrator device on each unit collects and desorbs VOCs in the whole-air sample, to allow for low detection limits on the (70 eV Electron Impact Ionization) Mass Spectrometers, typically operated in a full scan mode (45 to 250 AMU).

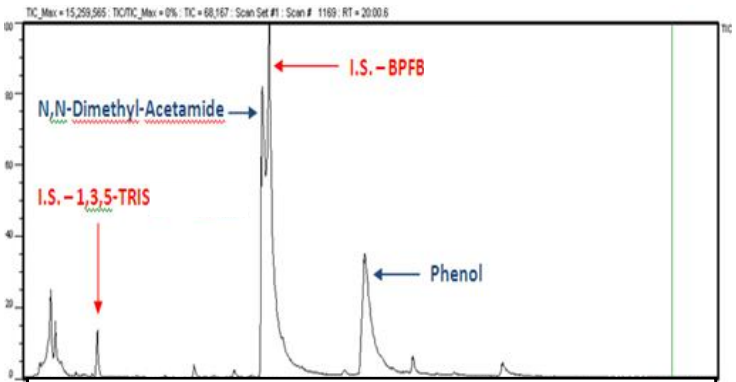
Air samples during this project were analyzed using a modified EPA TO-14 method in a full-scan mode, in which 170 mL of an air sample is concentrated on the tri-bed pre-column. The method is calibrated for 36 VOCs via a 4 to 6 point calibration curve with a %RSD of Relative Response Factors less than 30, consistent with the MassDEP Compendium of Analytical Methods (CAM). For TCE, the Reporting Limit (which is the lowest standard on the calibration curve) was 1 ppbV (5.4 µg/m^3), with “J” value results reported down to 0.2 ppbV (1 µg/m^3).

Each day, 10-mLs of a 100-ppbV TO-14 certified standard was injected into each unit as a daily calibration check standard, at the beginning of the 170 mL sample collection period (with the remainder of the sample comprised of research-grade nitrogen gas). This results in an effective check standard concentration of 5.9 ppbV (i.e., 10/170 x 100), which is in the lower-middle of the calibration curve. The units are assumed to be operating properly if the recoveries of key method analytes (e.g., TCE) are within 30% of the 5.9 ppbV concentration level.

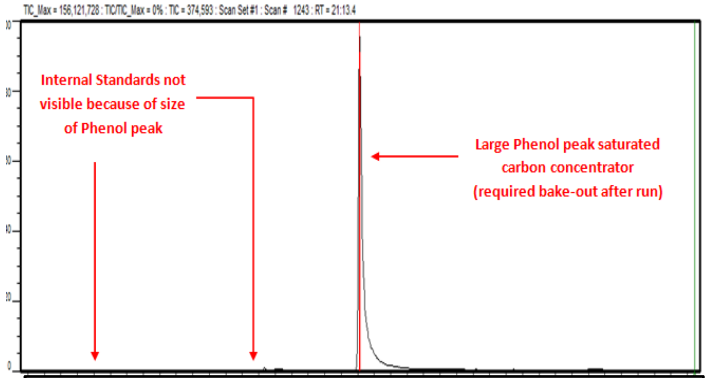
Air Sampling Bags

Indoor air samples were collected using an SKC “Grab Air Bag Sampler” pump, which was used to fill 1-Liter Kynar bags. At a pumping rate of about 0.5 to 1 Liter/min, it took between 1 and 2 minutes to obtain each “grab” sample.

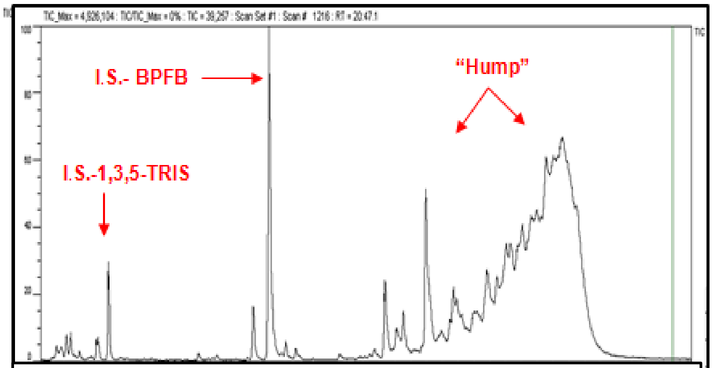
This method of sample collection and storage is clearly not as good as the use of evacuated passivated canisters. Sample “cross contamination” can occur if a highly contaminated sample sorbs analytes onto the sample pump. Sample bags can both desorb manufacturing impurities as well as sorb sample VOCs. Years of experience using the SKC pump has not suggested that sample carry-over is a significant issue. Conversely, years of experience and testing various bags have shown that air sampling bag integrity is more of a concern (See Figure 10).



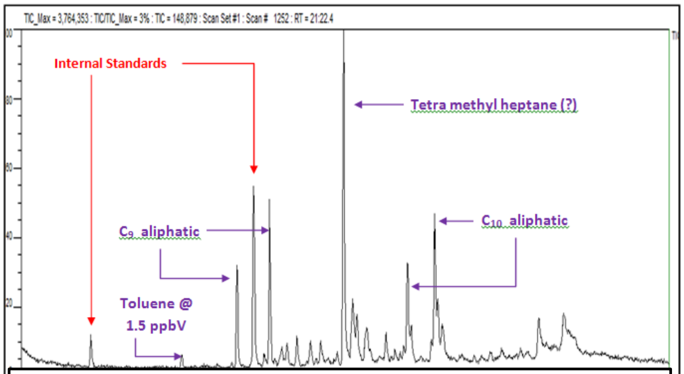
PVF (Tedlar) – Manufacturer “A”



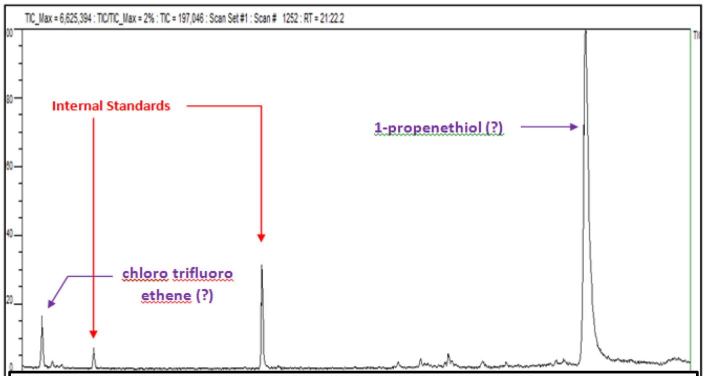
PVF (Tedlar) – Manufacturer “B”



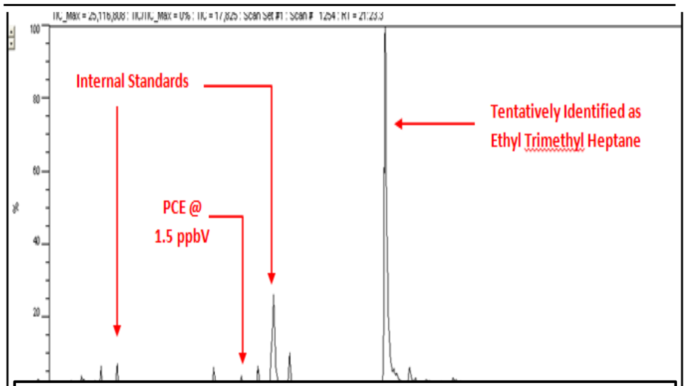
Proprietary Polymer – Manufacturer “C”



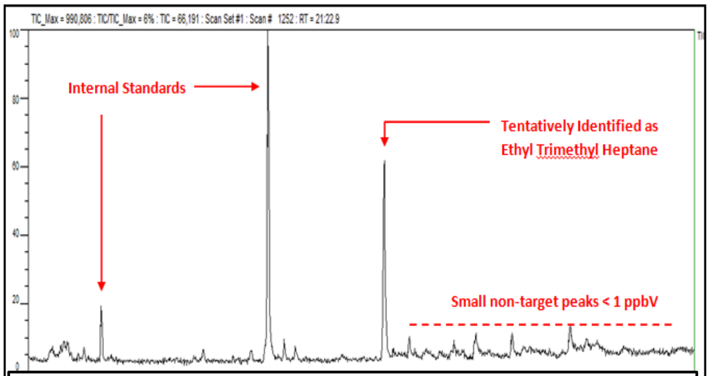
Foil type bag - Manufacturer “C”



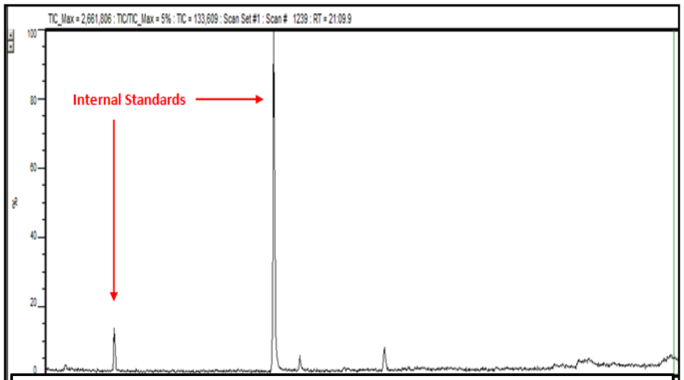
Proprietary Polymer – Manufacturer “D”



PVDF (Kynar) – Manufacturer “E”



PVDF (Kynar) –Manufacturer “B”



PVDF (Kynar) – Manufacturer “F”

Figure 10 – Contaminants Off-Gassing into 1-Liter Air Sampling Bags

Figure 10 illustrates the types of “bag contaminants” (manufacturing impurities*)* that are present in various bags from various manufacturers. These data are from the analysis of new bags that were filled with either zero air or research-grade nitrogen gas. All bags were analyzed within several hours of filling. All analyses were conducted on the MassDEP HAPSITE GC/MS units at various points between 2013 and 2016.

It is important to note that no bag off-gassed significant concentrations of common indoor air contaminants, such as PCE, TCE, or the BTEX compounds. However, in some cases, off-gassing contaminants interfered with the analysis of site samples (e.g., in Tedlar bags, high concentration of N,N-Dimethyl Acetamide interfered with the detection of an internal standard and thus quantification of certain method analytes, and very high concentrations of Phenol saturated the tri-bed concentrator). In other cases, hydrocarbon compounds off-gassing from the bag material complicated the assessment of indoor air petroleum vapors.

The reuse and flushing of bags (with research grade nitrogen) was seen to significantly reduce bag “background”. MassDEP FAST will clean and reuse bags as long as sample concentrations of VOCs are less than 5 ppbV. Moreover, 100% of re-used bags are filled with nitrogen gas and pre-tested, to ensure there is no significant carry-over of sample contaminants.

As presented in Figure 10, Tedlar, foil-type, and certain proprietary polymer bags were found to have the highest level of off-gassing bag contaminants. Kynar bags tended to have less contaminants, but the types and levels of such contaminants varied among different manufacturers. As can be seen, the Kynar bag from Manufacturer “F” was (by far) the “cleanest”; unfortunately, this manufacturer ceased making these bags in 2015; reportedly, there was an insufficient demand for the product, due to the fact that EPA (and other) publications had specified use of Tedlar bags. During the Newton project, the Kynar bags used were a combination of Manufacturers “F” and “B”.

Beyond off-gassing concerns, all bags will sorb sample contaminants to some degree. This phenomenon has been examined by MassDEP over the years, with significant differences noted between bag materials and brands. Figure 11 provides percent recoveries for the Knar bags used during the Newton Study.

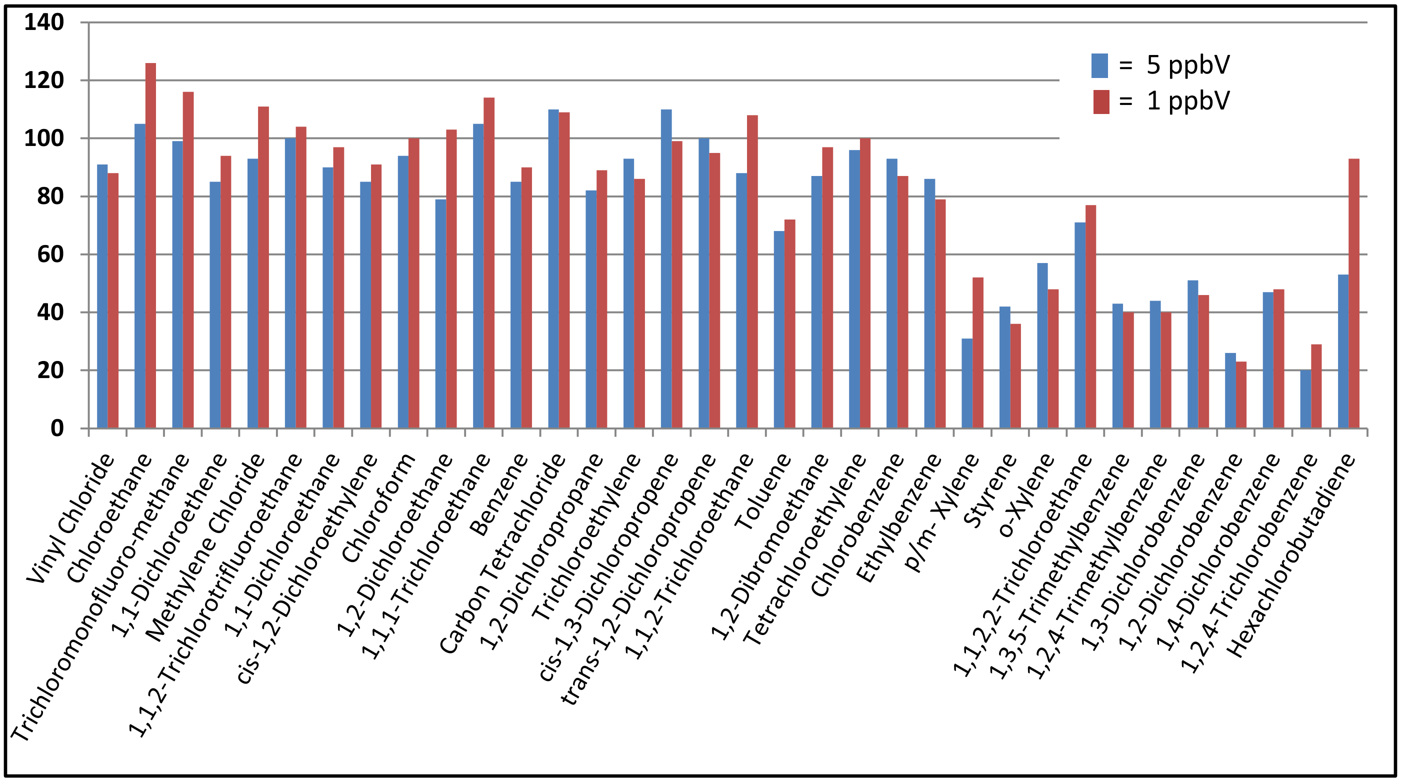


Figure 11- Percent Recovery of TO-14 Calibration Standards in Kynar Bags (May 2016)

The data presented in Figure 11 are for 1-liter Kynar bag samples filled with 400 mL of research-grade Nitrogen gas and subsequently "spiked" wither a 100 ppbV certified "TO-14" calibration gas standard in ratios to produce a 5 ppbV and 1 ppbV mixture within the bag. The prepared sample bags were then analyzed within about an hour on a HAPSITE GC/MS unit.

As can be seen, percent recoveries were good through Ethyl benzene, with a significant drop-off for the heavier molecular weight components beyond Ethyl benzene. This drop off has been noted with virtually all bags, which leads to a generic notation on bag analytical data reports indicating that actual concentrations of these heavier VOCs are likely 50% higher.

Of note are the good recoveries for TCE, at between 85% (1 ppbV standard) and 90% (5 ppbV standard).

Beyond initial sorption, concern also exists over sample integrity and bag holding times. While virtually all data obtained at the Newton site involved bag sample holding times of less than 24 hours, of interest was the effect of holding time on TCE stability in the 1-Liter Kynar bags. As such, samples from various homes were analyzed repeatedly over a 1 to 4 day period to discern these trends. These data are presented in Figure 12, and show that losses are higher concentrations (> 20 µg/m^3) are modest (<20%) during a 1 to 2 day holding time period, and relatively minor (<10% change) for lower concentration levels.

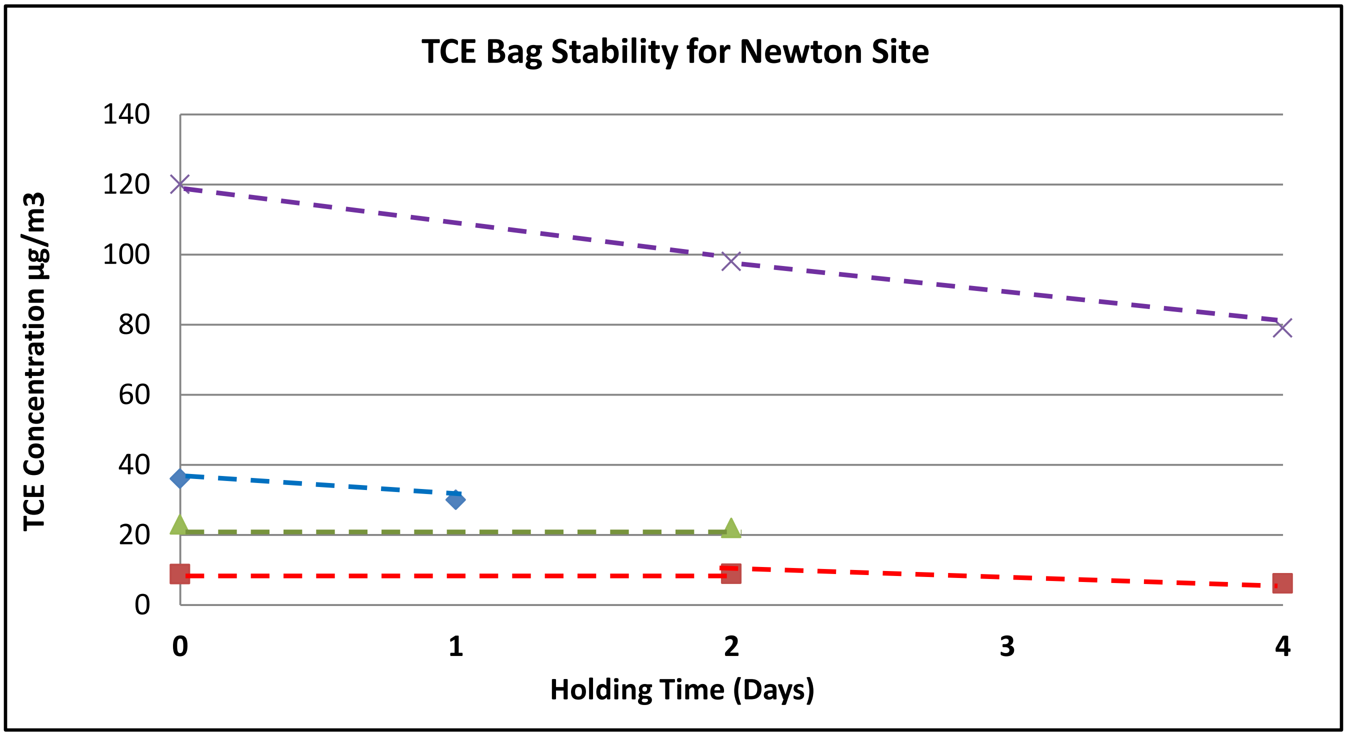


Figure 12 – TCE Stability in 1-Liter Kynar bags

Comparability to 24-hour TO-15 Data

The use of the FAST HAPSITE GC/MS units for the Newton project allowed for the generation of large amounts of indoor air quality data in a short amount of time – over 25 samples/day when both HAPSITE units were deployed in the field in the mobile laboratory. Beyond the immediacy – results were often obtained within a few hours of sampling – was the substantial cost savings (i.e., each 24-hour TO-15 sample analyzed by a contract laboratory cost $318 for the standard 6 to 10 day turn-around, and $480 for a "rush" 48-hour turn around – compared to an estimated cost of $75/sample on the HAPSITE units, which is inclusive of all instrument, supplies, and personnel costs).

Of interest is the comparability of the “conventional” TO-15 results to the HAPSITE results, and the utility of the HAPSITE grab/screening data in identifying Imminent Hazard conditions and monitoring mitigative actions. Accordingly, as part of this project, in addition to the 157 grab samples, 16 “conventional” 24-hour indoor air samples were also obtained by agency staff for TO-15 analysis by a contract laboratory, in order to provide confirmation of HAPSITE results, and provide a basis to compare both sets of data.

Table 1 compares 24-hour TO-15 data to HAPSITE grab sample data that was obtained on or (relatively) close to the 24-hour sampling period.

Table 1 – Comparison of HAPSITE Grab Data to 24-hour T0-15 Data

Address	Type Sample	Date	TCE		Other Contaminants - µg/m3		
			µg/m3	% Diff	cis 1,2-DCE	MeCl	Tol
West St home 1, Bsmt	Grab	11/22/14	10	10	<1	<1	1.9
	24 hr	11/24-25	11		0.2	<4.9	1.5
West St home 1, 1st Flr	Grab	11/22/14	<1	*	<1	<1	2.0
	24-hr	11/24-25	5.4		0.1	4.9	2.7
West St Duplex 1, Bsmt	Grab	11/24/14	180	41	5.2	2.6	2.9
	24-hr	11/24-25	107		3.4	4.9	1.8
West St Duplex 1, 1st Flr	Grabs	11/24/25 AVG	17	29	<1	1	3.0
	24-hr	11/24-25	12		0.4	<1	6.6
West St Duplex 2, 1st Flr	Grab	11/24/14	76	7	1.8	20	4.7
	24-hr	11/24-25	71		2.2	35	2.8
West St Duplex 2, Bsmt	Grabs	11/24-25 AVG	38	55	1	10	3.5
	24-hr	11/24-25	59		1.8	33	3.1
West St home 2, Bsmt	Grab	11/24/14	19	5	<1	11	4.4
	24-hr	11/24-25	18		0.5	22	4.6
West St home 2, 1st Flr	Grab	11/24/14	7.5	16	<1	3.3	2.5
	24-hr	11/24-25	8.7		0.2	8.6	7
Chapel St home 1, Bsmt	Grab	12/13/14	140	28	8	19	50
	24-hr	12/17-18	101		4.7	26	63
Chapel St home 1, 1st Flr	Grab	12/17/14	16**	69	<1	5.6	12
	24-hr	12/17-18	5.0		0.2	<1	6.7
Middle St Duplex 1, Bsmt	Grab	12/13/14	58	9	2.4	<1	1
	24-hr	12/17-18	53		1.6	<1	1.1
Middle St Duplex 1, 1st Flr	Grab	12/17/14	13	31	<1	<1	2.4
	24-hr	12/17-18	17		0.5	<1	1.5
Middle St Duplex 2, Bsmt	Grab	12/13/14	8.6	5	<1	<1	1
	24-hr	12/17-18	9.0		0.3	<1	4.0
Middle St Duplex 2, 1st Flr	Grab	12/17/14	6.3	33	<1	1.5	3.9
	TWA	12/22-23/14	8.4		0.3	<1	2.1
Chapel St home 2, Bsmt	Grab	2/11/15	N.D	0	<2	<1	2
	TWA	2/17-18/15	N.D.		<0.08	2.4	2.3
Chapel St home 2, 1st Flr	Grab	2/11/15	<1	0	<2	<1	1.8
	TWA	2/15-18/15	0.1		<0.08	4.3	2.2

* not deemed to be a relative metric given low levels and time between grab and TWA samples

** grab sample results from 12/13/14 were 2.9 and 3.5 µg/m^3

As can be seen, at 6 addresses (purple shading), the grab sample was obtained at some point during the 24-hour canister sampling period. At two additional addresses (green shading), a grab sample was obtained at the beginning and ending of the 24-hour canister sampling period, resulting in an average concentration value for the grab sample data point. At the other 8 addresses, the grab sample was obtained 2 to 6 days prior to the 24-hour canister sampling period.

Overall, the percent difference between the grab sample results and 24-hour canister results ranged from zero to 69 percent, with an overall R^2 value of 0.9163, as presented in Figure 13.

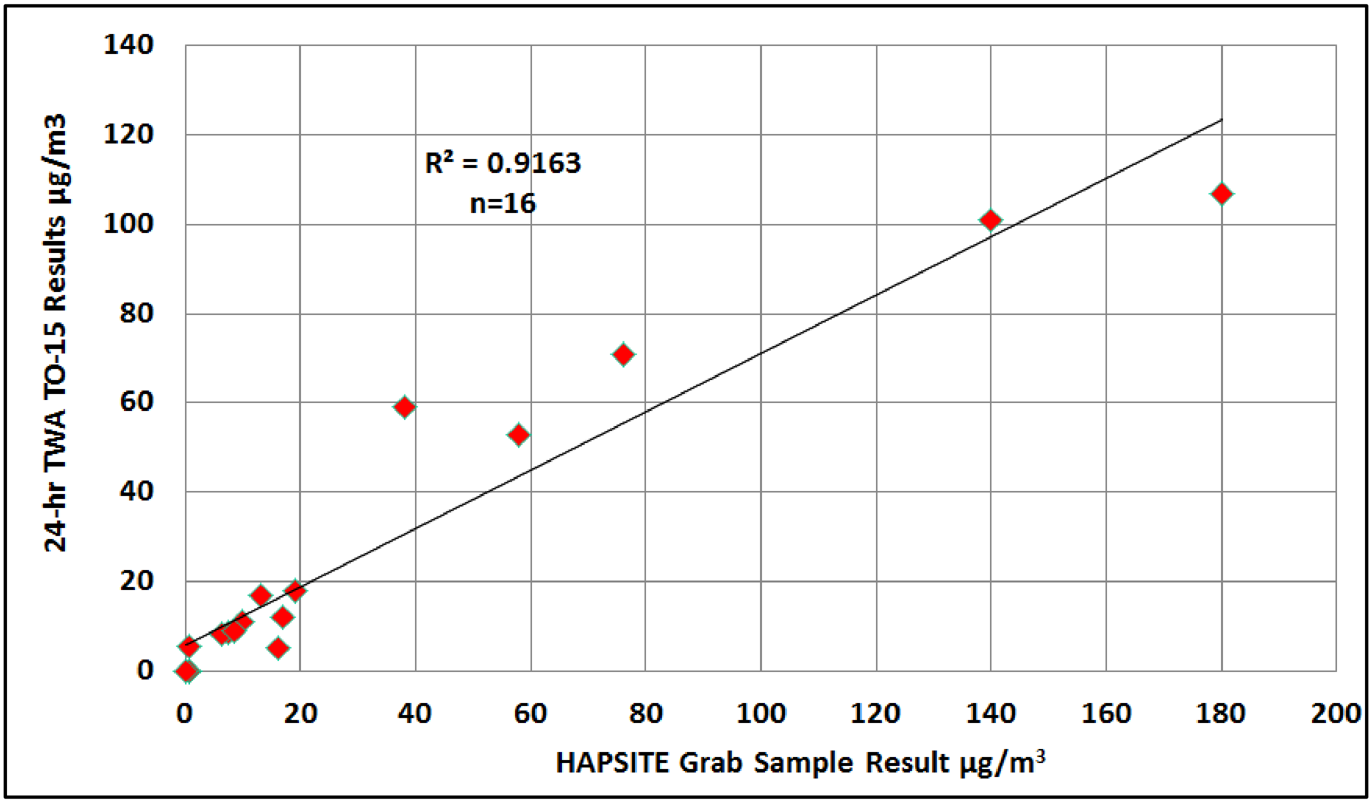


Figure 13 – HAPSITE GC/MS Grab Sample Results vs. 24-hour TO-15 Results – All Data Points

The most incongruous data pairing was for “Chapel St Home 1, 1st Flr”, where the grab sample from 12/17/14 at 16 µg/m^3 was significantly higher than the 24-hour result of 5 µg/m^3. It is worth noting that two previous grab samples from this location on 12/13/14 came back as 3.5 and 2.9 µg/m^3, suggesting that the 12/17/14 grab sample may had been an anomaly, perhaps due to airflow from the basement space prior to sampling.

Given that analytical variability alone can account for a difference of +/- 30% between data sets from different laboratories, the overall correlation between the grab and 24-hour data is reasonably good. Further analysis of the data points in Table 1 and Figure 13 suggests that this correlation is highest for spaces with the least air-exchange rates (i.e., basements) and when TCE concentrations are not highly elevated (e.g., < 100 µg/m^3). This is consistent with observations at a number of other sites where FAST grab sample data is compared to 8-hour or 24-hour time weighted data.

In looking at only the 8 basement air samples, the correlation between the 24-hour data and FAST grab sample data is very good (R^2 = 0.9515). When the two basements with levels of TCE greater than 100 µg/m^3 are excluded, the correlation is even better, as presented in Figure 14. And this includes a comparison between samples taken up to 6 days apart. This suggests that temporal variation in many basements (with low air exchange rates) may not be significant, even over a 4 to 6 day period.

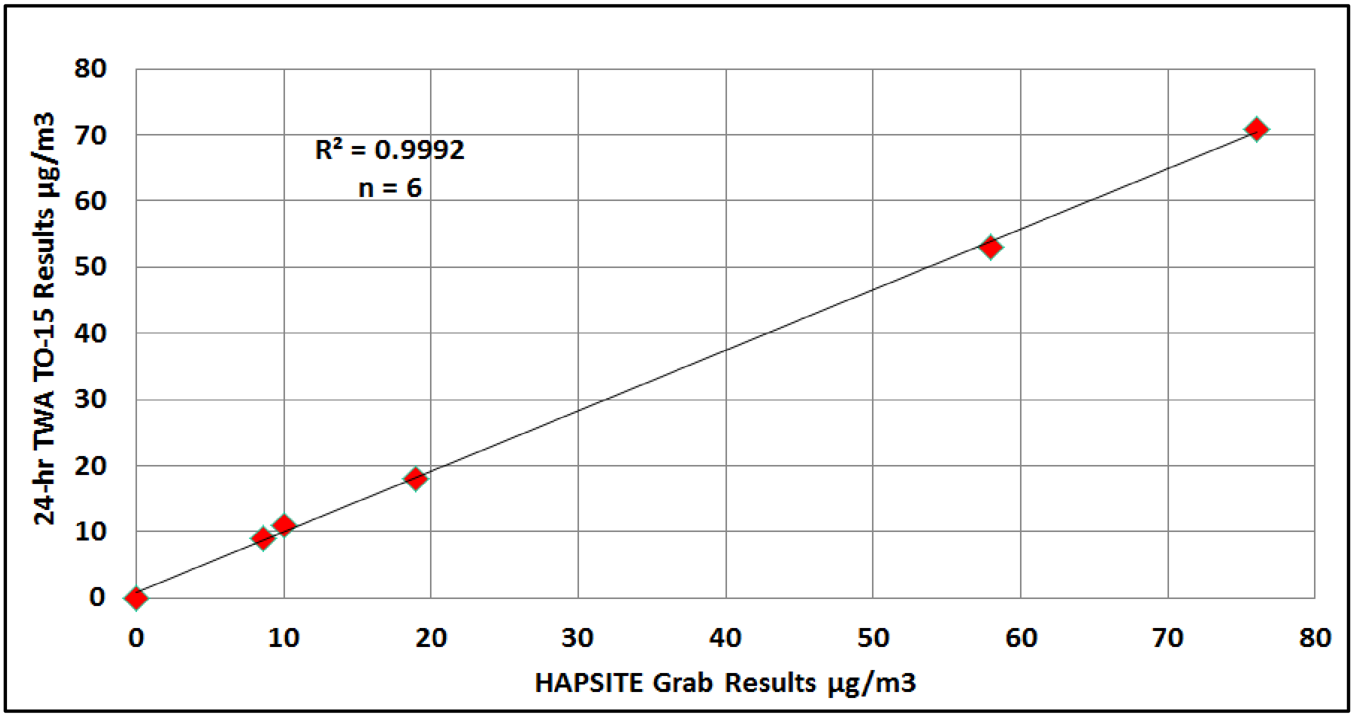


Figure 14 - HAPSITE GC/MS Grab Sample Results vs. 24-hour TO-15 Results–Basements with TCE < 100 µg/m^3

Many researchers have reported on the temporal variability issue, with the current presumption being that concentrations of VOCs within indoor air that originate from a vapor intrusion pathway can vary by more than an order magnitude over days or weeks, and up to 2 or even 3 orders of magnitude over the course of a year. The primary drivers in this regard are barometric pressure, temperature, winds, and the operation of fans/combustion appliances.

Temporal variability is the reason why many regulatory agencies require 24-hour composite indoor air samples for residential exposure assessment. While longer sampling periods will clearly equalize varying concentration conditions over the short term, how representative are these 24-hour samples in characterizing the long-term risk of exposures, and how much superior are these data to grab sample data?

The 16 data sets in Table 1 do not show a large overall variation between the grab and 24-hour data, during "worst case" cold weather conditions (i.e., November and December) – well below the "order of magnitude" changes of concern. The lack of 24-hour data in this case would NOT have resulted in a missed Imminent Hazard condition – though the 5.4 µg/m^3 value reported for the 24 hour data in West Street home1, 1st floor came close – if the 6 µg/m^3 value applied to this home (it did not), and if there were no other signs of concern (also not the case here, as the grab sample in the basement reported 10 µg/m^3, compared to 11 µg/m^3 reported in the 24-hour sample).

Another interesting trend can be seen in the data contained in Table 1, with respect to the variability between basement and 1st floor data. The average % Difference for the 8 pairs of basement samples was less than 15% - well within expected analytical variability. Conversely, the % Difference for the 6 pairs of 1st floor data was 3 times higher at 48%. This is consistent with the observation that the basements in all of these homes were unfinished and infrequently used, and thus unlikely to have a high air-exchange rate.

To further explore temporal variability in basement spaces, a resident of an impacted home was asked to obtain a 1-Liter sample of basement air on a daily basis (excluding weekends), typically in the evening. These samples were transported to MassDEP for analysis on the HAPSITE GC/MS units. These data are presented in Figure 15, together with the typical drivers of vapor intrusion (temperature, wind, barometric pressure).

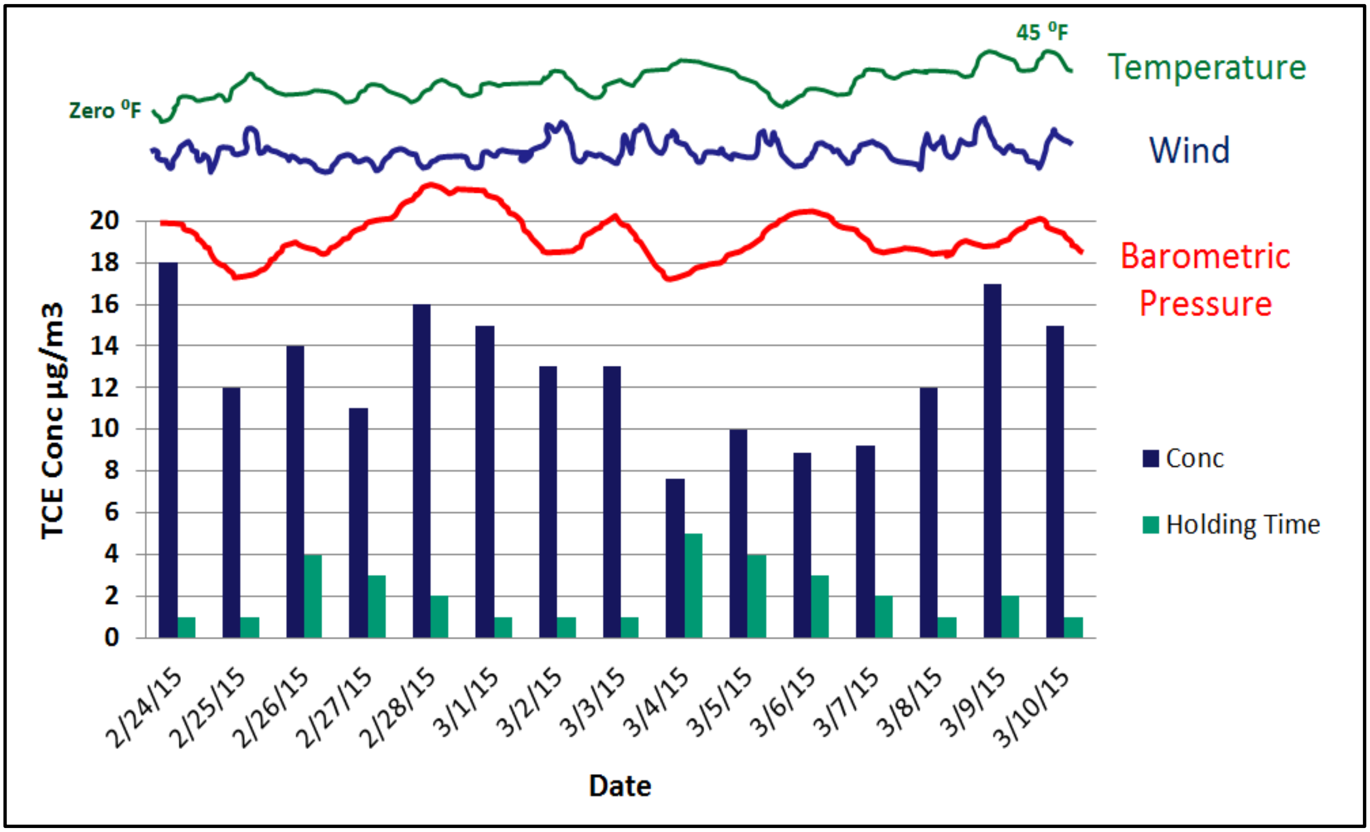


Figure 15 –Daily Basement Air Samples in an Impacted Home (Grab Data)

As can be seen, TCE concentrations varied between 8 and 18 µg/m^3, over an approximately 3 week period during late February/early March. Also of note is the holding times for each sample (in some cases the resident was unable to transport the samples in a timely manner). Given the likelihood that TCE data from samples held more than 2 days are biased low, this range is likely narrower, perhaps 12 to 18 µg/m^3, which is approaching the range of expected analytical variability.

Comparison of Indoor Air Sampling Locations (Basement vs. First Floor)

During the Newton project, grab indoor air samples were synoptically obtained in the basement and first floor of a residential dwelling, to help minimize the possibility of missing a vapor intrusion pathway.

Of the 19 homes in which TCE was detected, the TCE concentrations were higher in the basement than on the first floor in all but two cases. Based on 17 sets of "grab" data and 6 sets of "24 hour" data, TCE concentrations in the basement were an average of 17 times higher than on the first floor. This is not unexpected, given the mechanisms of vapor intrusion and attenuation within a structure.

Of the two homes that bucked this trend, one (on Chapel Street) had an active radon mitigation system in which the footprint of the basement was only about 50% of the footprint of the first floor. In this case, 2.3 µg/m^3 of TCE was measured on the first floor (in an area with no basement), compared to <1 µg/m^3 in the basement near the radon extraction pipe. The other home (also on Chapel Street) had 1.6 µg/m^3 of TCE in the basement compared to 2.3 µg/m^3 on the first floor – essentially the same value.

This finding indicates that in most cases, sampling only in the basement should be sufficient to identify a vapor intrusion pathway that may be creating an Imminent Hazard condition. However, concurrent sampling on the first floor would be recommended in unusual cases and/or if there are sensitive receptors in the dwelling.

Effectiveness of APU Devices

Deployment

Standard DEP protocol is to deploy activated-carbon Air Purifying Units (APUs) to immediately address and mitigate Imminent Hazard conditions, until such time as longer term measures (e.g., SSD system) can be implemented. The APUs deployed at this site were Austin Air *Healthmate Plus* models containing 15 pounds of an activated carbon/zeolite/potassium-iodide media at a 10:1:1 ratio. A schematic and a photo of this unit is provided in Figures 16 and 17. The activated carbon isotherm provided by the manufacturer is presented in Figure 18.

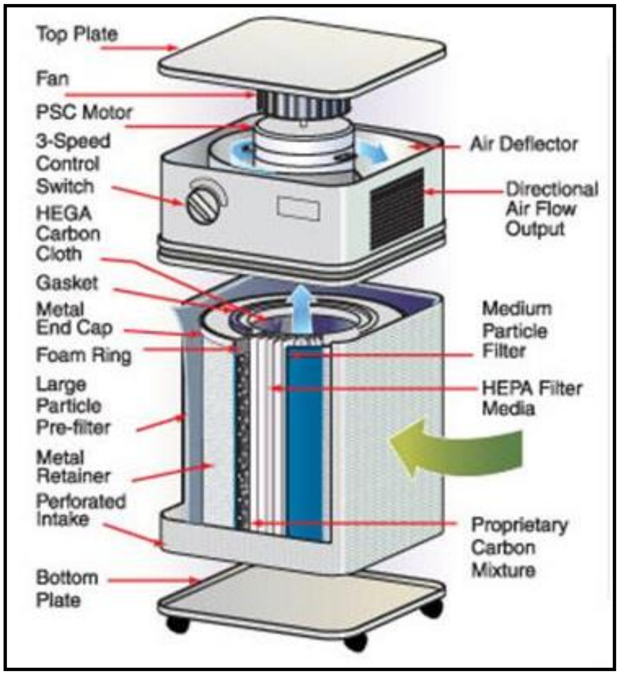


Figure 16 – Austin *Healthmate* APU

Figure 17 –APU in Chapel St Bsmt Apartment

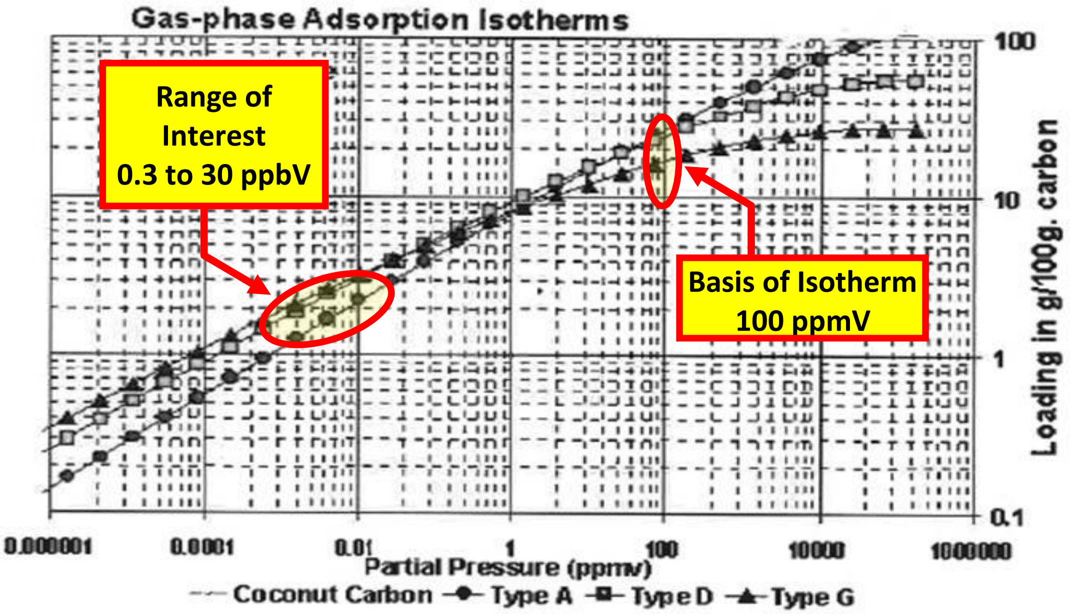


Figure 18 – TCE Isotherm Provided by Vendor for Activated Carbon in APU

A total of 8 APUs were deployed: 4 in basement spaces, and 4 in 1st floor spaces. Four of these units were deployed in a duplex on West Street; one in the basement and one of the first floors of each side of the duplex. Each APU was operated at the "medium" setting of 125 CFMs (use of the 250 CFM "high" setting was noisy and led some residents to shut off the units completely). Based upon the size of the space being treated (i.e., basement or 1st floor), this corresponded to about 1.5 to 2 air exchanges per hour.

At the time of APU activation, TCE concentrations in the basement spaces ranged from 71 to 120 $\mu g/m^3$; on the first floor spaces, 8 to 59 $\mu g/m^3$. A graph showing pre- and post-TCE concentrations in the treated spaces is presented in Figure 19 (Note – a post-activation trend is not provided for one of the basement spaces (Chapel St Bsmt) due a lack of data).

As shown in Figure 19, sharp reductions were noted in the first one to two weeks in the 3 basement spaces and in the 1st floor space that initially contained high concentrations of TCE (> 50 $\mu g/m^3$). These trend lines then significantly flattened, eventually achieving levels below or approaching 20 $\mu g/m^3$ after 7 to 10 weeks.

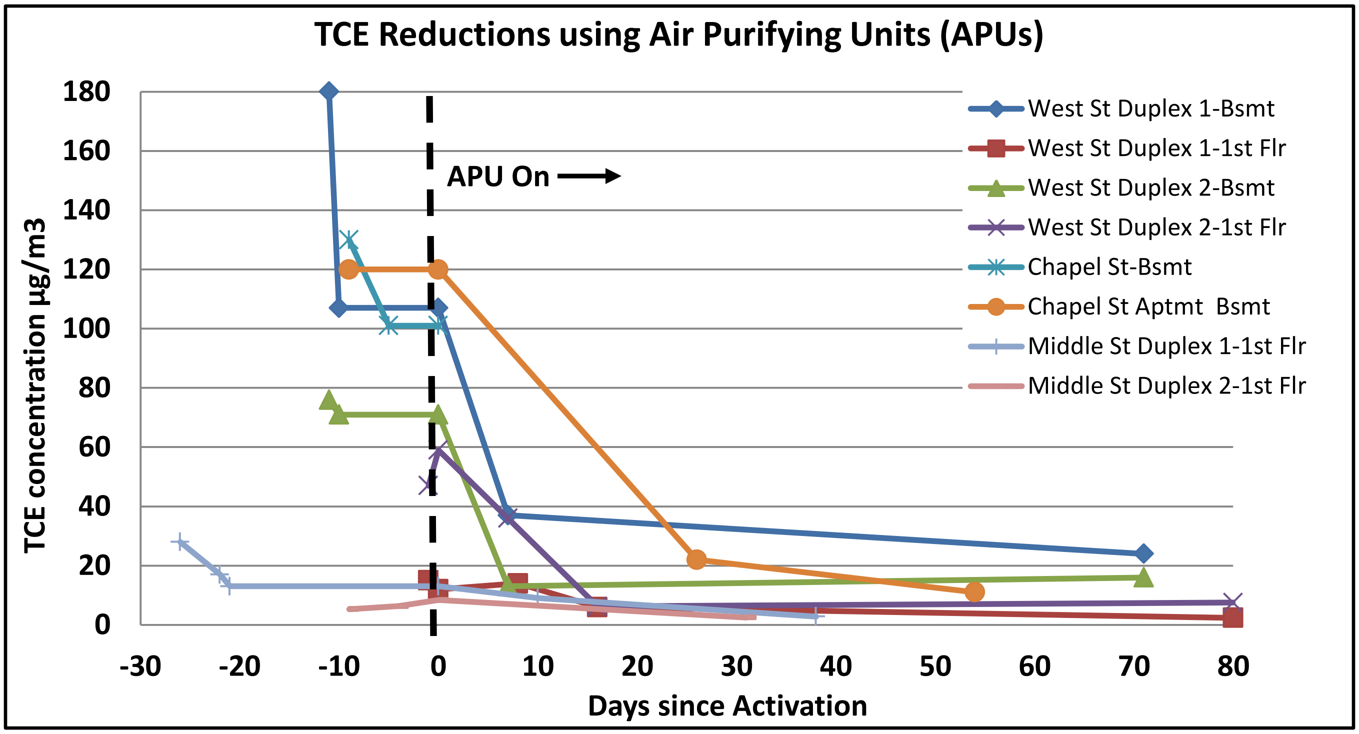


Figure 19 –Effectiveness of APUs in Reducing TCE Concentrations within Impacted Homes (Grab Data)

Reductions in those 1st floor spaces where TCE was initially present at less than 20 $\mu g/m^3$ were less immediate, with reductions to 6 $\mu g/m^3$ after 2 to 4 weeks, followed by a slow reduction to less than 3 $\mu g/m^3$ after 7 to 10 weeks.

Of interest is not only the rate but also the extent of TCE reduction in each of the spaces treated by an APU.

There were of course many variables in each space that was treated that could influence the rate and/or extent of sorption. These included initial TCE concentration levels, mass flux inputs from the subsurface/underlying basement, humidity levels, the presence of other indoor air contaminants, air circulation patterns, indoor/outdoor air exchange rates, and air exchange between the basement and first floor spaces (especially the West Street duplex with APUs in both the basements and fist floors). Despite these variations, what was remarkably similar was the percent reduction of TCE over the 60 to 80 day post-activation monitoring period: about 80%.

This is graphically presented in Figure 20.

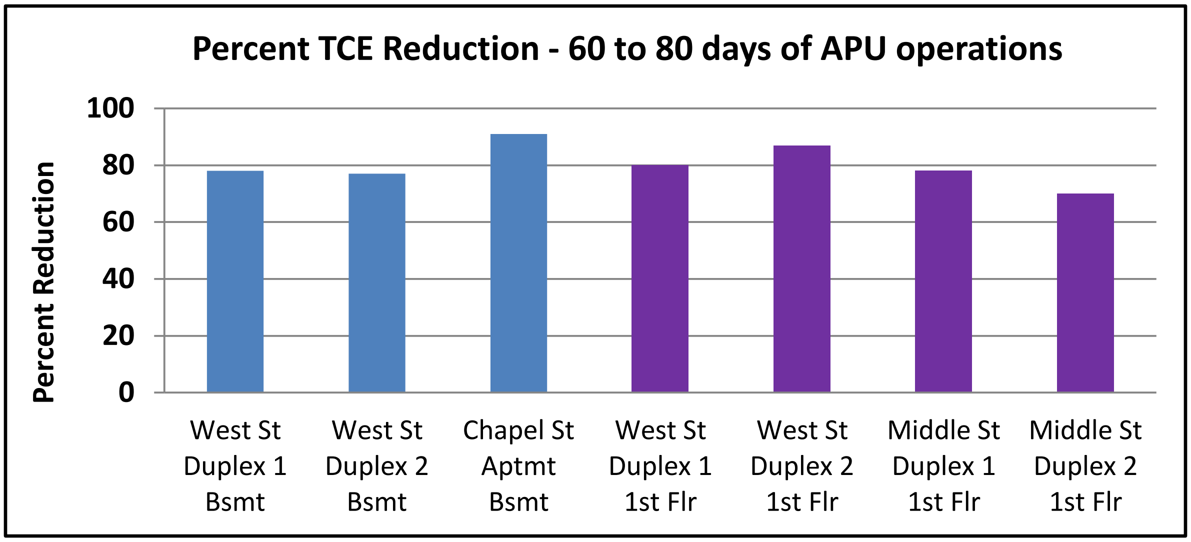


Figure 20 –Percent Reduction in TCE Post-APU Activation (Grab Data)

Low-Level APU Removal Rate Evaluation

To further assess removal rates at low concentration levels, an experiment was conducted in the basement of Middle Street Duplex #1, which contained levels of TCE more than 6 µg/m^3 and less than 20 µg/m^3 - the range of interest. This is the same home that was used to assess temporal variability (Figure 15), which provided the baseline condition prior to the deployment and activation of a Healthmate Plus APU in the basement (Note: an APU had previously been installed in the first floor of this home, but not the basement).

The APU was installed and activated on the evening of March 11th. Daily pre- and post-APU activation indoor air data for TCE are presented in Figure 21.

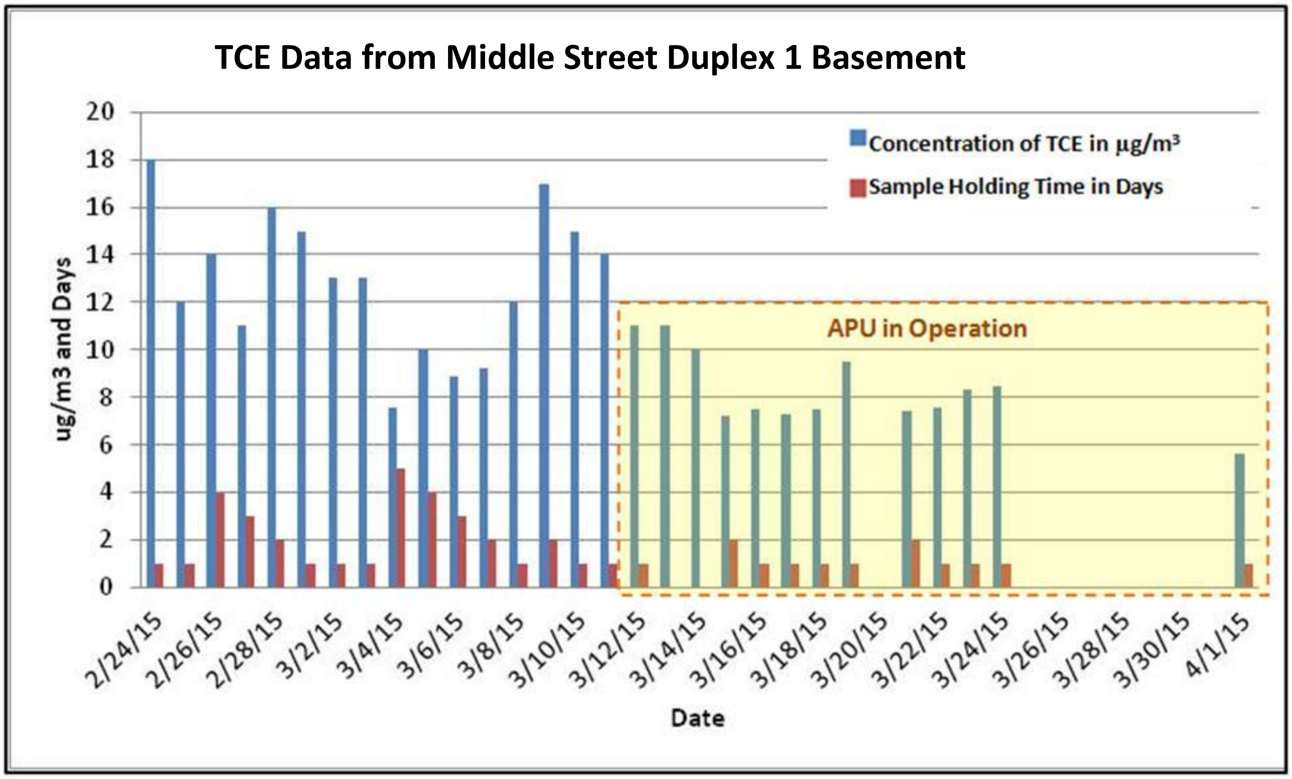


Figure 21 –APU Study Conducted in Basement of Impacted Home (Grab Data)

As can be seen, baseline concentrations of TCE in this basement had been fluctuating between about 12 and 17 µg/m^3, with an average value around 14 µg/m^3 (taking into account the sample hold times). A week after the activation of the APU, levels of TCE appeared to have dropped by about 40%, to an average of about 8 µg/m^3. Eight days later, on April 1st, TCE was measured at about 6 µg/m^3, an apparent continuation of the slow decline following APU activation, consistent with the long-term data contained in Figure 19. Even though this was a basement space, several discrete measurements conducted over the course of the experiment documented Relative Humidity levels of less than 50%, consistent with winter conditions and the deep water table (15+/- feet below basement slab) at this location.

Activated Carbon Considerations

The performance and utility of common activated-carbon APUs – both at the Newton site and other sites – is of particular interest for TCE, given toxicological concerns over even short term exposures to sensitive receptors. As such, can/how long will it take for these units to achieve desired concentration levels (< 6 µg/m^3)?

While activated-carbon has long been used to treat VOCs in air, it's efficacy in removing the relatively low concentrations of concern in the vapor intrusion pathway is not well understood, *as there is virtually* no *published information or data on the performance of these systems or filters at these low (< 50 ppbV) concentration levels.* (Yao et. al, 2009; Vizhemehr, 2014).

It is worth noting that isotherm data and design information and guidance on vapor-phase filters are based upon/extrapolated from experiments conducted at high ppmV concentration levels – the industry (ASHRAE) standard is 100 ppmV – 4 to 5 orders of magnitude higher than levels of concern at vapor intrusion sites. Conceptually, there is reason to believe that there may be significant differences in the extent and/or rates of adsorption at low ppbV concentrations.

Specifically, the pores within activated carbon are broadly defined as "micropores" (≤ 20 Å), "mesopores" (≤500 Å), and "macropores" (>500 Å). Adsorption in the micropores plays a significant role in the removal of VOCs typically found within indoor air, as contaminant molecules tend to sorb the strongest in areas where the pore diameter is similar to the molecular diameter of the VOC compound, which allows for multiple contact points on the absorbent surface. This includes TCE, a planar molecule with approximate dimensions of 6.6 Å x 6.2 Å x 3.6 Å, as depicted in Figure 22. Based upon the slit-shape geometry of activated carbon pores, the planar TCE molecule is thought to diffuse in a flat form into the deep portions of the micropores (Karanfil and Dastgheib, 2004).

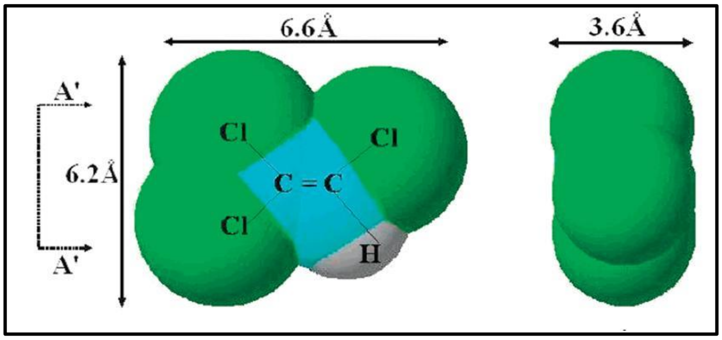


Figure 22 – Molecular Dimensions of TCE

For VOCs such as TCE, physical adsorption (not chemisorption) is the predominant mass-transfer/contaminant removal mechanism. Physical adsorption is the result of weak intermolecular attractive (*van der Waals*) forces that arise from rapid fluctuations in electron clouds that induce dipole moments and create positive/negative attractions between neighboring atoms. These forces become stronger with increasing molecular weight, as outer shell electrons become more distant from the nucleus.

In an activated carbon filter, VOC removal takes place in 3 stages. In the first stage, VOC contaminants move through the filter media via bulk/turbulent air flow until they encounter an unsaturated boundary layer around a portion of a carbon particle. In the second stage, VOCs migrate into and through macropores via molecular diffusion (i.e., collisions between VOC molecules), and into and through a micropore via Knudsen diffusion (i.e., collisions that occur between the VOC molecules and pore walls). Finally, in the third and last stage, adsorption takes place at the gas/solid interface. As this third (adsorption) step is rapid, the overall mass transfer rate is controlled largely by the first two stages. While movement from the turbulent flow in stage 1 to the laminar flow in stage 2 can be optimized by adjusting the bulk air flowrate through the filter, the diffusive movement in stage 2 is a function of VOC concentration - a significant issue for low (ppbV) concentrations of VOCs in indoor air, as diffusive rates and thus the rate of adsorption decreases with decreasing VOC concentration (Yao et.al., 2009).

Assuming that the activated carbon had not become saturated by the low-ppbV loading rate, it would appear that the stage 2 diffusive flux is the rate-limiting step. Accordingly, increasing the throughput would not accelerate the removal process; what is needed is additional carbon.

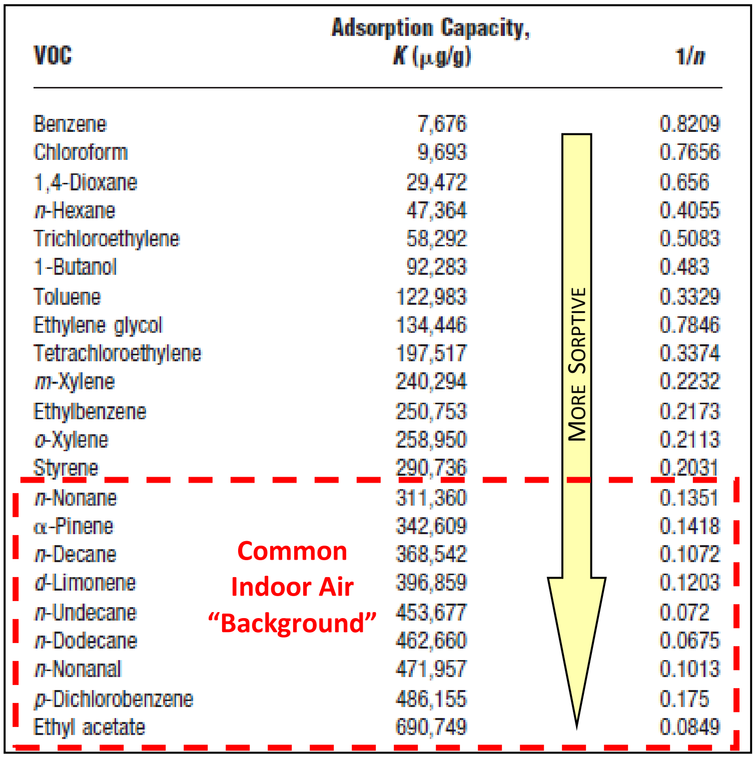
Indoor Air Considerations

Two additional factors can have a significant effect on the rate and extent of sorption: the presence of water vapor (humidity), and the presence of "common" indoor air contaminants (e.g., ethyl acetate) that compete with vapor intrusion contaminants (e.g., TCE) for sorption sites.

It has long been known that the presence of water vapor in air can reduce the rate and amount of VOC adsorption on activated carbon filters. This is due to:

- water molecules sorbing onto available sites on/within the activated carbon; and
- the capillary condensation of water vapors in micropores, which can "block" movement of VOCs into these spaces.

This phenomenon can also affect the types of VOCs that get removed by the filter, as the presence of water vapor can enhance the removal of polar contaminants (e.g., MEK) via their dissolution into capillary pore water. Importantly, the deleterious impacts of water vapor appear to be modest below a Relative Humidity value of 50%. Conversely, the negative effects of water vapor appear to increase with decreasing contaminant concentrations (Vizhemehr, 2014).



VOC	Adsorption Capacity, *K* (μg/g)	1/*n*
Benzene	7,676	0.8209
Chloroform	9,693	0.7656
1,4-Dioxane	29,472	0.656
n-Hexane	47,364	0.4055
Trichloroethylene	58,292	0.5083
1-Butanol	92,283	0.483
Toluene	122,983	0.3329
Ethylene glycol	134,446	0.7846
Tetrachloroethylene	197,517	0.3374
m-Xylene	240,294	0.2232
Ethylbenzene	250,753	0.2173
o-Xylene	258,950	0.2113
Styrene	290,736	0.2031
n-Nonane	311,360	0.1351
α-Pinene	342,609	0.1418
n-Decane	368,542	0.1072
d-Limonene	396,859	0.1203
n-Undecane	453,677	0.072
n-Dodecane	462,660	0.0675
n-Nonanal	471,957	0.1013
p-Dichlorobenzene	486,155	0.175
Ethyl acetate	690,749	0.0849

Figure 23 – Relative Sorptive Affinities (Yao et. al., 2009)

While compounds such as TCE can be the primary or only contaminant of concern or interest at a site, other chemicals which may be present in the indoor air will compete for sorption sites on the activated carbon filter media. In general, compounds having a molecular weight greater than 50 and a boiling point greater than 50° C will sorb to greater or lesser degrees, with sorptive affinity generally increasing with increasing molecular weight and/or increasing boiling point (Shepherd, 2001).

The significance of this issue is illustrated in Figure 23, which presents the Freundlich isotherm parameter (1/*n*) and adsorptive capacities (µg/g) in an activated carbon sample for TCE and common indoor air "background" contaminants, including *d*-limonene, *n*-dodecane, and ethyl acetate. In addition to having a significantly higher sorptive affinity, these compounds can also be present within indoor air at significantly higher concentrations than vapor intrusion VOCs such as TCE. Compounding this concern is the possibility that these large molecular weight compounds can block the micropores that most strongly attract the smaller VOCs such as TCE.

Most of these common indoor air “background” compounds are not Target Analytes in EPA Method TO-15, and their (tentative) presence and (approximate) concentrations will not be disclosed by a laboratory unless specifically requested. Absent this information and design consideration, the effectiveness and design life of activated carbon APUs can be significantly less than predicted.

APU Considerations

The Healthmate APU, like many similar products, is comprised of an external rectangular casing housing a replaceable cylindrical activated carbon filter. The replaceable filter contains 15 pounds of an activated carbon/zeolite/potassium-iodide media at a 10:1:1 ratio (see Figure 24).

Figure 24 – Healthmate APU and Removable Filter

The filter is composed of two layers, and is surrounded by a pre-filter cloth that is inserted between the filter and the walls of the APU. A blower on top of the unit creates a negative pressure inside of the cylindrical filter, inducing a 360^0 inflow of room air.

The activated carbon layer is about 13.5 inches in outer diameter and 14.5 inches in height, resulting in a surface area of approximately 4 ft^2, with a “flow through” thickness of 2 inches.

Though composed primarily of activated carbon, this layer also contains Zeolite (to absorb moisture) and, in the “Plus” unit, potassium iodide (KI), to provide enhanced chemisorption of certain organic compounds (e.g., formaldehyde). At a 10:1:1 ratio of components, each filter contained 12.5 pounds of activated carbon.

At a flow rate of 125 CFMs, the uniform velocity of air through the carbon filter would be 31 feet/min (125 CFM/4 square feet).

Observations

The monitoring data obtained for the 8 APUs deployed at the Newton site are consistent with the presumption that the sorptive rate-controlling step is the migration of VOCs (TCE) into and through macropores via molecular diffusion, and into and through a micropore via Knudsen diffusion. This diffusive flux is a function of VOC (TCE) concentration, and as such the rate of sorption will slow as the concentration of VOCs (TCE) decreases, resulting in an exponential decay of indoor air VOC (TCE) concentrations.

How quickly will levels of TCE be reduced? At this site, each APU containing 12.5 pounds of activated carbon treated a space of between 3500 to and 5500 cubic feet, operating at 125 CFM; about 1.5 to 2 air exchanges/hour. Initial levels of TCE in the range of 60 $\mu g/m^3$ to 120 $\mu g/m^3$ were seen to decline by 50 to 75% after about 1 week of operation; for initial levels of TCE between 6 $\mu g/m^3$ and 20 $\mu g/m^3$, a decline of 50 to 75% took about 2 weeks. After 7 to 10 weeks of operation, all units (regardless of the initial concentration of TCE) had obtained reductions of about 80% - which meant that those spaces where TCE was the highest (> 60 $\mu g/m^3$) did not achieve the 6 $\mu g/m^3$ goal even after 7 to 10 weeks. It is not clear if continued operation beyond this timeframe would continue to lead to further reductions in TCE concentrations.

It is worth noting that at this site (deep groundwater) during the time period of evaluation (winter), Relative Humidity values were likely below 50% at all times. Moreover, an evaluation of the total ion chromatograms for the spaces undergoing treatment did not disclose the presence of high concentrations of extraneous “background” VOCs that would compete with TCE for sorptive sites. As such, the evaluation conditions were likely a “best case” situation.

Based upon the above, 12.5 pounds of activated carbon does not appear to be sufficient to reduce concentrations of TCE to level less than 6 $\mu g/m^3$ in less than 1 week, unless the initial concentrations of TCE are less than 10 to 15 $\mu g/m^3$. For higher concentrations, additional units/activated carbon may be able to achieve this goal. For very high concentration levels (e.g., > 50 $\mu g/m^3$), one unit in the basement and two on the first floor may be appropriate (assuming the basement is not used as a living space).

Even more activated carbon/units may be needed if high humidity (> 50% RH) or elevated “household” VOCs are present. Both concerns should be considered when planning an APU deployment.

SUB-SLAB DEPRESSURIZATION (SSD) SYSTEMS

While the use of APUs are an expedient and prudent first step to mitigate vapor intrusion impacts, the installation and activation of SSD systems are generally necessary to effectively achieve and maintain the low-levels of TCE (and other VOCs) needed to ensure protection of human health.

SSD systems were required in 4 structures in Newton, including 2 structures with “Duplex” residential units, 1 single family home, and 1 large single family home that had been converted into apartments, including a basement apartment. In order to reduce costs, detailed design and installation specifications were developed by MassDEP, and the project was put out to bid, with the hope of attracting the interest of radon mitigation contractors, and increase competition (now and in the future).

The radon mitigation industry is well-established, with a substantial number of independent contractors and trade/professional associations. There are a large number of publications on how to design, install, and operate the SSD systems used to mitigate radon (vapor) intrusion, including from the US EPA and ASTM, dating back to the early 1990s. That being said, there appears to be a significant degree of variability in the industry on how these systems are installed, with respect to fan size/selection/placement, piping diameter/thickness, sump construction, venting locations, etc., with the most significant area of departure between practitioners and EPA/ trade publications being pre-installation sub-slab diagnostic communication tests.

It appears that most radon mitigation contractors do not conduct the recommended pumping tests to determine pressure/flow relationships and optimize fan selection. Rather, the Transmissivity of sub-slab vapors are often discerned from simply viewing sub-slab fill materials, sometimes combined with a trial-and-error use of several different fan units that are maintained by contractors and transported to each job site. On occasion, a "shop vac" test may be conducted to evaluate pressure field extension at distant probes, but with little consideration for the fact that a shop vac develops 50 to 90 inches w.c. of negative pressure, compared to the 1 to 4 inches w.c. negative pressure achieved by most radon fans.

Despite these practices, many contractors maintain that systems installed in this manner are adequate, given that post-installation reductions in radon (and VOCs) meet (or eventually meet) design objectives. There is some evidence to support this point of view in the Newton study area: of the 6 homes with pre-existing radon systems in the heart of the TCE vapor intrusion zone, 4 had levels of TCE < 1 $\mu g/m^3$, and only 1 exceeded the 6 $\mu g/m^3$ Imminent Hazard value.

Such a position is however not persuasive, given that properly conducted diagnostic testing (and head loss calculations in proposed piping networks) can be used optimize fan and piping selection, to minimize long-term electrical costs, and better ensure that system performance will be adequate "from the start", without the need for call-backs and modifications. This is especially important for TCE, where even a few weeks of elevated exposures are undesirable. Accordingly, the EPA-recommended diagnostic testing procedures were undertaken during the design of the Newton systems, along with an evaluation of head loss in the proposed piping networks.

Sub-Slab Diagnostic/Communication Testing

Similar to groundwater "pump tests" that are undertaken to evaluate aquifer conditions, the movement of another fluid - air beneath a basement floor - can be characterized by establishing a relationship between the applied vacuum, resultant flowrate, and resultant negative pressure conditions in subslab probes. While this can be accomplished using a variable-speed fan, it is less expensive and more convenient to use a standard shop-vac connected to an extraction pipe with a "tee" fitting and ball valve "bleed".

Methods and Materials

The diagnostic extraction device used in Newton is diagramed in Figure 25; a photograph of the apparatus in use in a basement on West Street is provided in Figure 26. As can be seen, the extraction pipe apparatus was constructed of 2-inch diameter Schedule 40 PVC piping with 2-90^{o} elbows and a 2-inch to 1½ -inch reducing tee, with a 1½ -inch PVC ball valve connected to the tee.

A 2-inch diameter PVC coupling was attached to the bottom of the apparatus, and a small piece of 2-inch PVC piping was placed into the other end of the coupling. This small piece of 2-inch PVC piping was inserted into a 2 5/8-inch diameter hole cored into a concrete slab. The outer diameter of the 2-inch PVC coupling is slightly larger than the 2 5/8-inch diameter hole which secures the apparatus in place.

A brass barbed fitting (Watts LFA-192 ¼ "x ¼ " MIP) was installed at the bottom of the extraction pipe apparatus to allow vacuum measurements by a manometer or magnehelic gauge ("pressure port"). A small (9/64") hole was drilled in the pipe 26 inches from the pressure port to allow for the insertion of a Pitot tube (to measure flowrate). To conduct a diagnostic test, the 2-inch PVC extraction pipe was inserted into a cored-hole in a concrete basement floor. A bead of electrical duct seal putty was applied around the perimeter of the 2-inch PVC coupling to ensure a tight connection. With the inlet to the shop vac connected to the 2-inch rubber coupling and the 1½ -inch ball valve completely closed, the full negative pressure of the shop vac (generally around 50 inches of w.c.) was applied to the sub-slab. The precise vacuum was determined by connecting a magnehelic gauge to the pressure port barbed fitting.

Next, a Dwyer® Series 160 Stainless Steel pocket size Pitot tube (1/8- inch diameter with 6 inch insertion length) was inserted into the 9/64" hole (see Figures 25 and 26). An Infiltec digital micro-manometer was connected to the Pitot Tube to determine the difference between the total and static air pressure within the 2 inch pipe (ΔP), which is equivalent to the velocity pressure. The velocity pressure can then be converted to a feet/min velocity value by use of the Bernoulli equation. Finally, a CFM flowrate can then be calculated by multiplying the velocity (ft/min) by the cross-sectional area of the 2 inch PVC pipe (ft^2) to obtain a flowrate value in CFM.

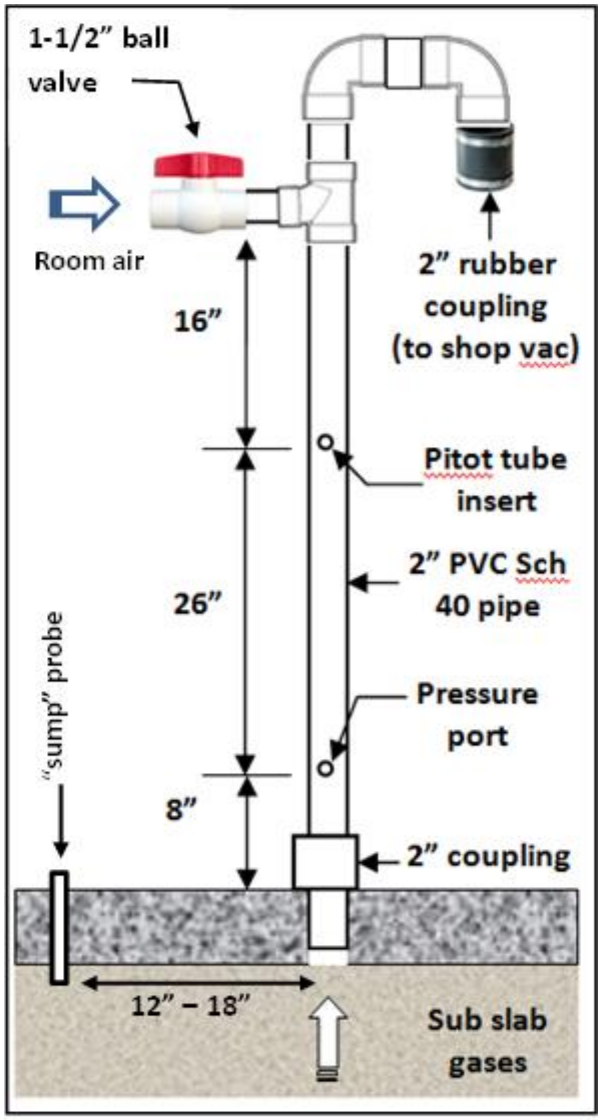


Figure 25 – Diagnostic Apparatus

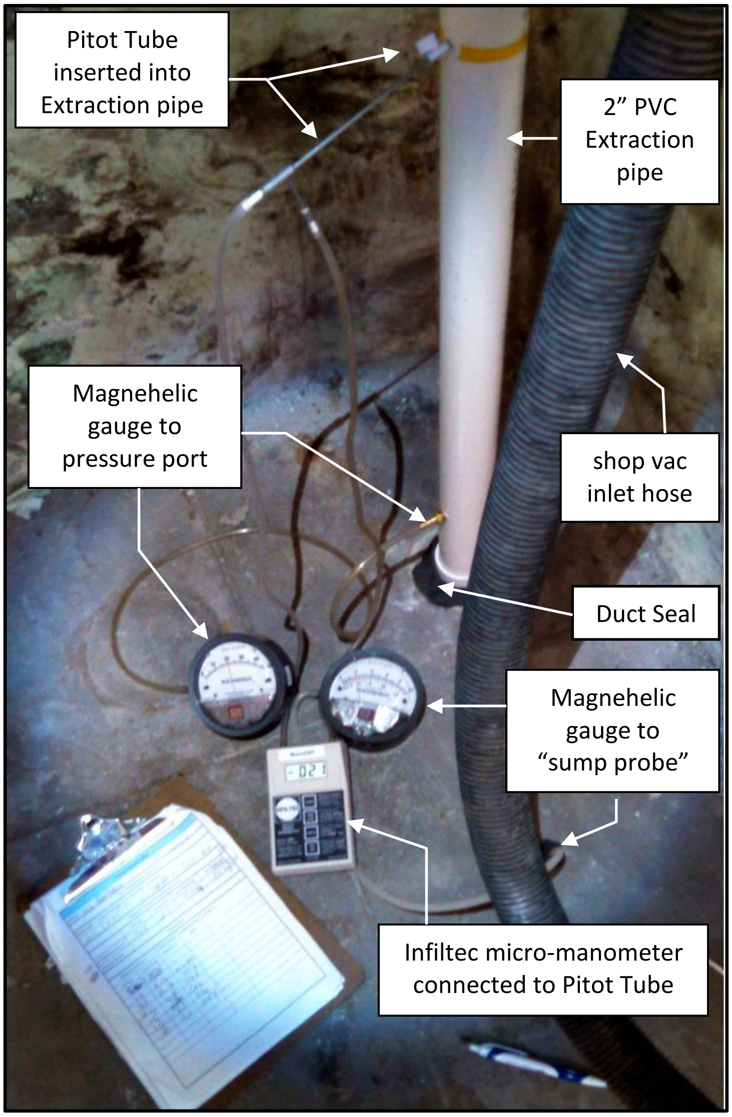


Figure 26 – Diagnostic Apparatus in West Street Bsmt

In some cases (e.g., West Street), a third measurement was made: the vacuum in a temporary sub-slab probe installed 12 to 18-inches from the 2-inch diameter extraction test hole. This point ("sump probe") was used to simulate the sub-slab vacuum that would exist at that point when a (12-inch to 18-inch diameter) sump is created as part of the installation of the permanent SSDS Extraction point.

At other sites (Middle and Chapel Streets), the diagnostic test was conducted on a fully-excavated sump with a 4-inch diameter slab core. In these cases, a Lexan cover was sealed to the slab, and the 2-inch PVC extraction apparatus was installed into a 2 5/8-inch hole drilled through the Lexan.

In both cases, after the initial vacuum/flow measurements were made, the 1 ½ -inch ball valve was partially opened, which "bled" basement air into the extraction pipe, resulting in a reduction in the vacuum applied to the extraction hole/sump and thus a reduction in the flow of gases from the sub slab. At that point, all vacuum and flow measurements were repeated (including negative pressure readings in sub-slab probes). This continued over a series of 4 to 6 increments, until the 1½ -inch ball valve was completely open, resulting in a 4 to 6 vacuum/flowrate data sets. Throughout this process*, the discharge from the shop vac was directed outdoors using hoses and piping.*

Calculating Flowrate Using a Pitot Tube

A schematic of the Pitot tube measurement process is provided in Figure 27; a schematic of the relevant parameters and equations is provided in Figure 28.

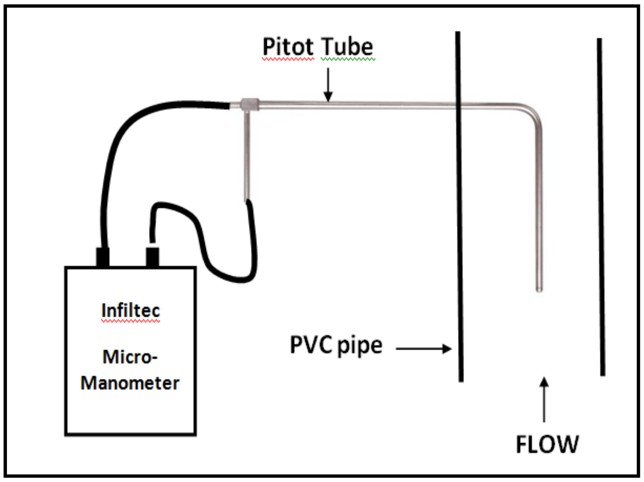


Figure 27 – Flow Measurement with Pitot tube

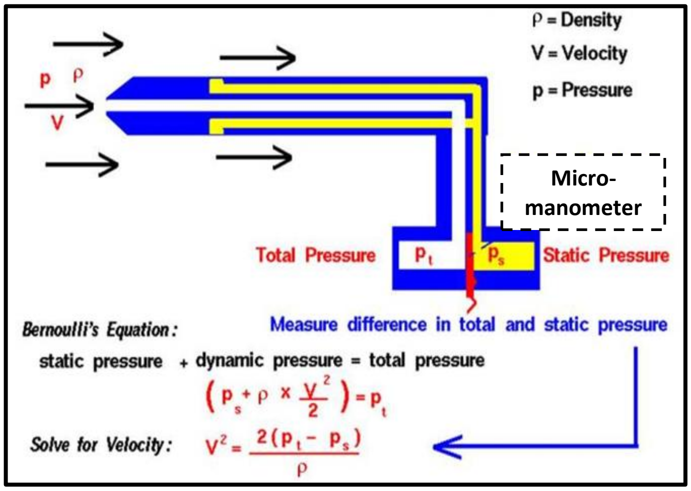


Figure 28 – Calculating Flowrate with Pitot Tube

According to the Bernoulli equation, for fluids flowing through a conduit, the total pressure at any point is equal to the static pressure plus the dynamic pressure.

A Pitot tube measures the difference between the total and static pressures ($\Delta P = P_d = P_t - P_s$), which is the dynamic pressure. It is then possible to solve for velocity using the Bernoulli equation, and, once velocity is determined, flowrate can be calculated using the continuity equation ($Q = V * A$).

In the Bernoulli equation, density (ρ) varies somewhat based upon temperature, humidity, barometric pressure, and even VOC concentration. However, a general estimate of 0.075 $\mathrm{lb/ft^3}$ can be used with reasonable accuracy (i.e., +/- about 2% of true value), to simplify the process.

Although using a Pitot tube is simple, flow through a pipe is not. Skin friction creates diminished flows near the walls of the pipe. Elbows and other obstructions create turbulence that further alters flow.

Ideally, a series of measurements should be made throughout the cross-section of a pipe transverse to the flow direction (to get an average value considering skin friction) and in multiple locations in the piping run (to account for turbulence). However, experience has shown that flow turbulence is minimal in straight sections of pipes at locations at least 8 to 10 pipe diameters downstream of an obstruction and at least 2 pipe diameters before an obstruction (which is why the extraction pipe apparatus is over 4 feet long). Moreover, correction factors have also been developed to convert a single Pitot tube measurement in the center of a pipe to an average cross-section value.

A number of Bernoulli/Pitot tube calculators can be found on the internet (including on the Dwyer web site). These convert ΔP measurements to velocity and then to flowrate. However, a simple one-step factor has been developed by radon researcher Bill Brodhead (http://wpb-radon.com/Measuring_airflow.html) that was based on actual measurements made on Schedule 40 PVC piping with a single Pitot tube measurement in the center of the pipe. These equations only require the input of the Pitot tube measurement (ΔP) in units of inches of w.c., and are specific to the diameter of the PVC piping:

For 2 inch diameter PVC pipes: $\text{CFM} = \sqrt{\Delta P}\ \text{x}\ 91$

For 3 inch diameter PVC pipes: $\text{CFM} = \sqrt{\Delta P}\ \text{x}\ 210$

For 4 inch diameter PVC pipes: $\text{CFM} = \sqrt{\Delta P}\ \text{x}\ 294$

It is noted that the formula from Mr. Brodhead produces results that are similar but slightly lower than other Pitot tube calculators (e.g., from Dwyer). A decision was made to use the Brodhead equations due to the empirical nature of his research.

Subslab Resistance

Vacuum/flowrate data from the enhanced diagnostic extractions tests can be used to create a vacuum/flowrate graph, which represents a *Subslab Resistance Curve*. In this context, the vacuum is the reading in the extraction sump, either presumed (in the case of using a "sump probe" 12 to 18 inches from a 2 inch diameter extraction hole) or actual (when a full 12 to 18 inch diameter sump is excavated and the diagnostic test is conducted through a 2 inch diameter hole in Lexan covering the sump).

Examples of the Subslab Resistance Curves created from the vacuum/flow diagnostic data in Newton are provided below in Figure 29.

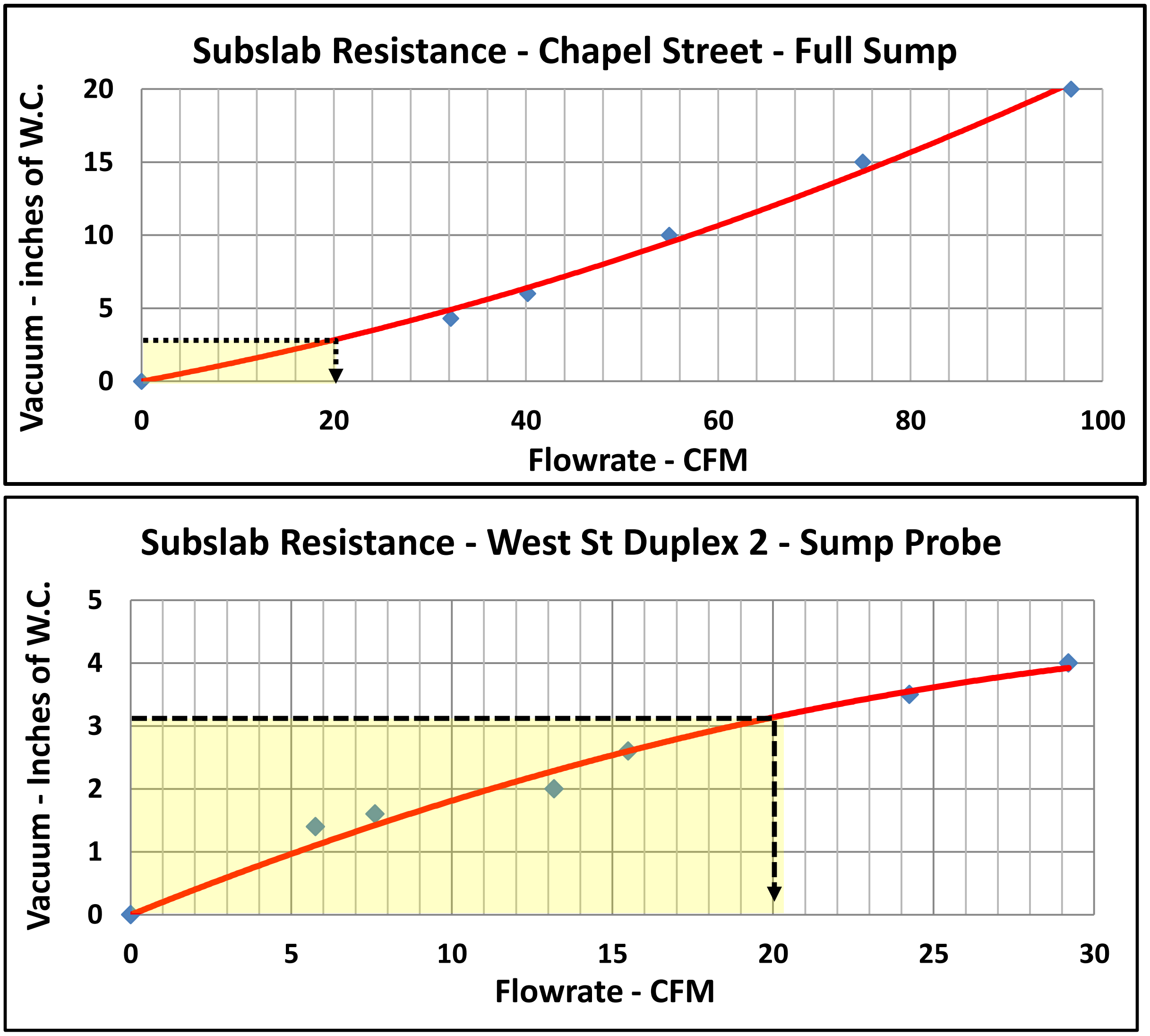


Figure 29 – Examples of Sub-slab Resistance Curves from Diagnostic Tests

All of the Subslab Resistance Curves from the Newton project reflect the “tight” subslab fill conditions observed in all 4 buildings (i.e., dense/poorly sorted fine sands with many cobbles). Even when the diagnostic test was conducted in a fully excavated sump, it took 12 to 20-inches of w.c. vacuum to induce 100 CFM of flow. It is speculated that the preponderance of 1 to 4-inch diameter cobbles “cemented” into the very dense sands resulted in a low effective porosity condition that significantly impeded subsurface airflow.

Of interest is the difference in the curves between the diagnostic test data from fully excavated sumps vs a 2-inch diameter coring. As indicated, the “Y” axis vacuum value for the latter scenario was the negative pressure recorded in a temporary “sump probe” located 12 to 18-inches from a 2-inch cored hole (with the premise being that the value in the “sump probe” will simulate the negative pressure in a fully excavated sump). As can be seen, the vacuum/flowrate graphs for the fully excavated sumps reflect much higher vacuums and flowrates, which is not unexpected. However, there was relatively good agreement between all of the graphs at 3-inches of water column vacuum (yellow shading on graphs) which are in the range of 20 to 25 CFM. Thus, while the fully excavated sump scenarios produced broader graphs with more pressure/flow relationships at high vacuum levels (i.e., 15 to 20-inches of w.c.), all scenarios produced similar results and information for the range of vacuum reflective of the most commonly used radon fans (i.e., up to 4 inches of w.c.). This suggest that “sump probe” assumptions for diagnostic tests conducted on a 2-inch coring (i.e., not on a fully excavated 12 to 18-inch diameter sump) is adequate for most sites, though conducting the diagnostic test on a fully excavated sump may be advisable when a high suction fan (> 4-inches of w.c.) is being considered.

For reference, note that the highest vacuum value measured in the 2-inch diameter Extraction pipe apparatus “pressure port” was 39-inches of w.c. (which produced 4-inches of w.c. vacuum in the sump probe in a West Street building. This is consistent with the performance of most shop vacs, which have a maximum (0 CFM) vacuum of between 40 and 60-inches of w.c.

Piping Network Head Losses

An SSDS suction fan must overcome not only the resistance inherent in the movement and removal of gases from the subsurface, but also the head losses generated by the subsequent transport of those gases through the 30 to 100-foot piping of typical SSD systems. For a given fan, these piping head losses will reduce the amount of suction that will ultimately be developed in the extraction sump, which will in turn reduce the extent and/or intensity of the negative pressure field beneath the slab. These combined forces are the (total) System Resistance.

(Total) System Resistance = Subslab Resistance + Piping Network Head Losses

Thus, in selecting a fan, the proposed piping network should be considered – including whether the piping will be 3-inch or 4-inches in diameter, as head loss in piping is a function of velocity, which in turn is a function of flowrate and pipe diameter. While financially and logistically the use of 3-inch diameter PVC pipes is preferred over the use of 4-inch diameter pipes, at higher flowrates (> 60 CFM), head losses are substantially more pronounced in 3-inch diameter pipes than in 4-inch diameter pipes. Conversely, at flowrates less than 20 CFM, the difference in head loss between 3-inch and 4-inch diameter piping is generally insignificant.

Of course, pressure and flow are directly related. A low flowrate is generally a sign of “tight” subslab soils and a “steep” Subslab Resistance Curve. For these tight conditions – such as in Newton – not only will the head loss between 3-inch and 4-inch piping be generally insignificant, both will also be a small and generally insignificant fraction of the subslab resistance, which will be the controlling factor in fan selection.

To illustrate this condition, and develop a methodology to address network head loss concerns at other sites with higher flowrates, *System Resistance Curves* were developed for the Newton SSD systems, by calculating head losses for proposed systems for both-3 inch and 4-inch diameter piping networks, and adding those losses to the Subslab Resistance Curves.

Initially, the Darcy-Weisbach equation was used to calculate head loss through a straight pipe. An English-units version of this equation incorporating assumptions and simplifying factors for PVC SSD systems has been published by Peramaki in *Proceedings of the Seventh National Outdoor Action Conference and Exposition on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods*, 1993. The basic equation is:

$$\Delta P_{fr} = f_d\ (12in/ft)(L/D)p_v$$

where:

ΔP_{fr} = friction/head losses in terms of total pressure (inches of w.c.)
f_d = friction factor (dimensionless)
L = pipe length (ft)
D = diameter of pipe (inches)
P_v = velocity pressure (inches of w.c.)

The velocity pressure (P_v) can be calculated using the following equation, assuming the vapor density of the air in the piping is 0.075 lbs/ft^3:

$$p_v = (V/4005)^2$$

where:

V = average air velocity in pipe (ft/min)

The calculation of the friction factor (f_d) depends on whether air flow through the pipe is classified as laminar flow, transitional flow, or turbulent flow. This in turns requires the calculation of the Reynold's Number (N_r) for any given combination of flow and fluid viscosity per the following relationship:

$$N_r = DV/\upsilon$$

where:

Nr = Reynold's Number (dimensionless)
D = diameter of pipe (ft)
V = average fluid velocity (ft/min)
ν = kinematic viscosity (assume 9.84×10^{-3} ft^2/min for standard air)

Most PVC SSD systems operate under turbulent flow conditions. In these cases, the friction factor (f_d) is a function of the Reynold's Number (N_r).

Within the range of $4000 < Nr < 100{,}000$:

$$f_d = 0.3164/N_r^{0.25}$$

When the Reynold's number (N_r) is > 100,000:

$$f_d = 0.0032 + 0.331/N_r^{0.237}$$

In rare cases (very low flowrates), flow in PVC SSD system may be laminar ($N_r \leq 2000$). In those cases,

$$f_d = 64/Nr$$

Finally, on occasion, flow in PVC SSD systems may be in the transitional range between laminar and turbulent. In these cases, the calculation of the friction factor becomes complicated. However, the use of the Swamee-Jain equation provides a more simplified option to estimate this factor. This degree of simplification and approximation is appropriate given the relatively rare occurrence of transitional flow and given the overall level of precisions and accuracy in the diagnostic and design procedures.

In accordance with the Swamee-Jain equation, for transitional flow:

$$f_d = 0.25 \left[log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Nr^{0.9}}\right)\right]^{-2}$$

where:

ε = pipe roughness (0.000005 ft for PVC)
D = pipe diameter (ft)
N_r = Reynold's number (dimensionless)

This can be further simplified to an assumed f_d value of 0.044 for 4-inch diameter PVC pipes and 0.045 for 3-inch diameter PVC pipes

With the above equations and assumptions, the head loss can be calculated for flow through straight piping. However, all SSD systems will include elbows and other components and fittings which must also be considered.

The mechanisms of head loss in elbows and fittings are different from those in straight piping. While the pressure drop in straight piping is due primarily to frictional losses, head losses from elbows and fittings are due primarily to dynamic losses induced by the change of flow direction and patterns. These dynamic losses are also referred to as "local losses", and are theoretically complex. As such, they are generally calculated using empirical methods.

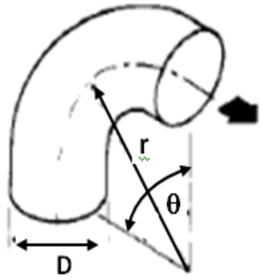
One of the most widely used empirical approaches is from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), which calculates local losses from fittings and elbows using the following equation:

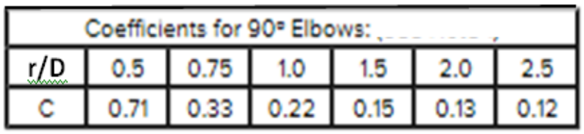
$$\Delta P_f = (C)(P_v)$$

where:

ΔP_f = Dynamic Head Loss for a fitting (inches of w.c.)
C = Fitting Loss Coefficient (dimensionless)
P_v = Velocity Pressure (inches of w.c.)

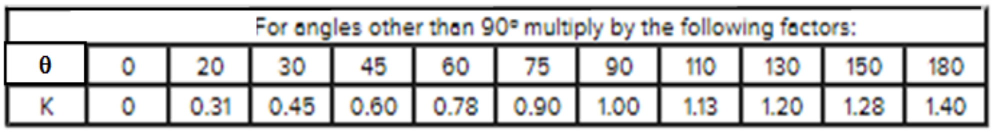
The Fitting Loss Coefficient (C) for elbows is a function of the ratio of the turning radius (r) to the pipe diameter (D). The recommended values (ASHRAE) for a 90° elbow are provided in the first table below. The second table provides additional modifying factors for fittings with angles (θ) other than 90°.





Coefficients for 90° Elbows:

r/D	0.5	0.75	1.0	1.5	2.0	2.5
C	0.71	0.33	0.22	0.15	0.13	0.12



For angles other than 90° multiply by the following factors:

θ	0	20	30	45	60	75	90	110	130	150	180
K	0	0.31	0.45	0.60	0.78	0.90	1.00	1.13	1.20	1.28	1.40

Fitting Loss Coefficient (C)			
Size	Fitting	r/D	C
3"	90	1.021	0.22
3"	long 90	1.35	0.3
3"	45	0.58	0.49
4"	90	0.946	0.21
4"	long 90	1.23	0.27
4"	45	0.55	0.47

Inputting the radius (r) and diameter (D) values for the Schedule 40 PVC elbows manufactured by the Charlotte Pipe Company – a major supplier of PVC plumbing supplies in the US – yields the Coefficient (C) values in the table to the right for the most common fittings in the most common pipe sizes for SSD systems.

Using the Darcy-Weisbach equation and ASHRAE fitting loss equation, the total head loss for SSD system piping networks can be calculated.

Total System Resistance

The total system resistance is the summation of head losses from the extraction of the subslab gases and head losses in transporting those gases through the piping network to a discharge point above the roof of a structure.

An excel spreadsheet was developed to calculate piping network head losses for any given combination of straight PVC pipe and 90^o and 45^o elbows. The spreadsheet will automatically plot and overlay 4 curves:

- the Subslab Resistance Curve reflective of the vacuum/flow relationships from the diagnostic testing;
- Negative pressure trends in the subslab probes monitored during diagnostic testing;
- the (total) System Resistance Curve if a 3-inch diameter PVC piping network is used; and
- the (total) System Resistance Curve if a 4-inch diameter PVC piping network is used.

These graphs may be used to select the piping size, and then select the optimum fan, by overlaying the performance curves of up to 3 candidate fans to discern the optimum choice.

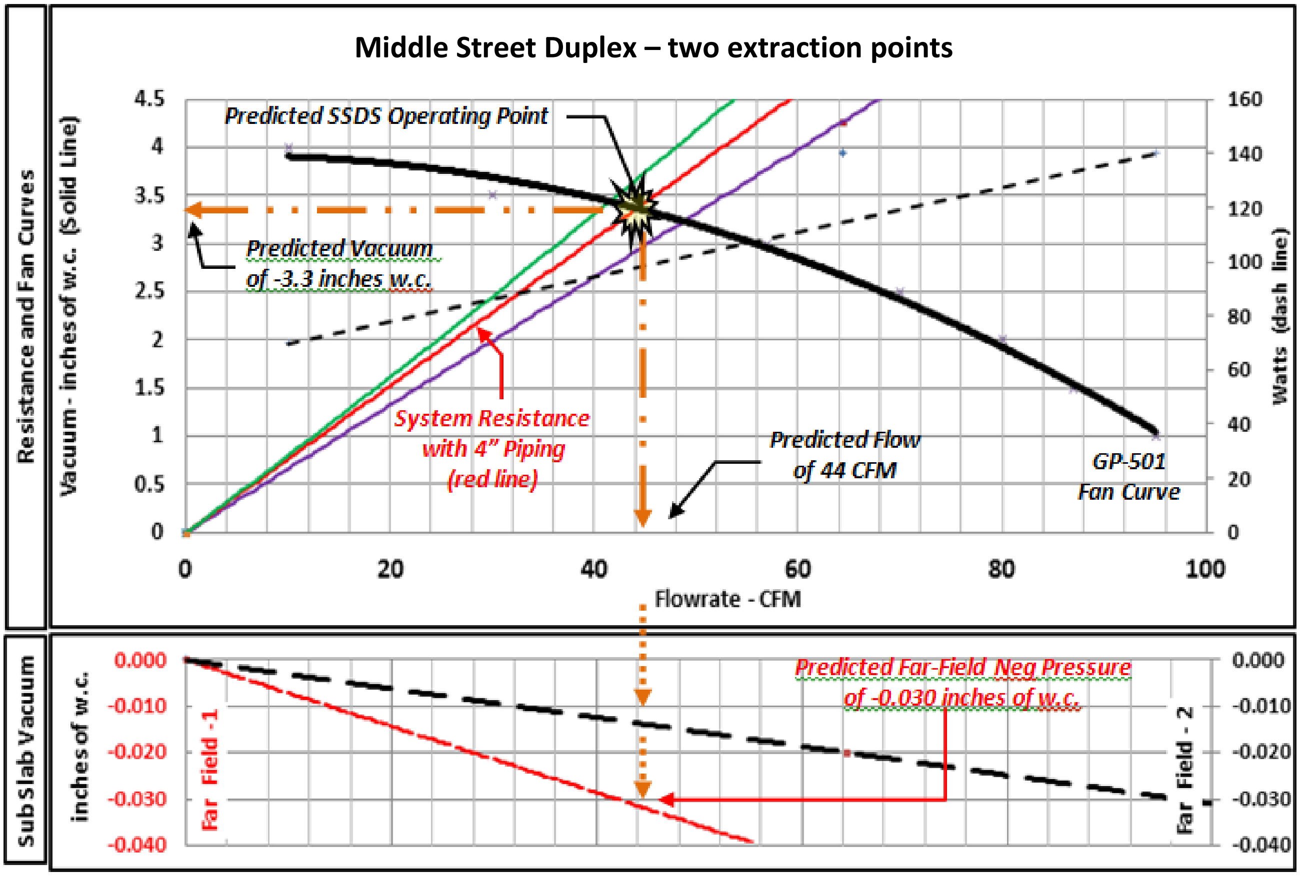
An example of this exercise is presented in Figure 30 for a duplex residential structure on Middle Street in Newton. At this site, two extraction points were installed and piped to a single extraction fan/discharge point. All piping was 4 inch diameter PVC, and a Randonaway GP-501 fan was selected by the contractor.

This graph shows the system resistance curve (purple), along with the total system resistance for a 4 inch (red line) or 3 inch (green line) diameter PVC piping network. The negative pressure in two far-field sub-slab probes are also graphed for the corresponding pressure/flow conditions of the fan. The curve for the GP-501 fan overlays the system resistance curves; a dashed line represents the power (watts) usage corresponding to the flowrate plotted on the “x” axis.

Predicted vs Actual System Performance

In theory, the operating state of the fans and sytems (i.e.,pressure and flowrates) should be at the intersection of the System Resistance Curve and the Fan Curve. In the example presented for the Middle Street Duplex in Figure 30, the system would be expected to operate at a flowrate of about 45 CFM, producing -3.3 inches w.c. vacuum in the extraction sump pit. At this flowrate/vacuum, the negative pressure in the far-field sub-slab probes would be estimated to be -0.01 and 0.03 inches w.c. The power usuage would be about 100 watts.

In Table 2, the actual operating conditions for the five SSD systems are tabulated, along with the predictive values discerned from the diagnostic testing and spreadsheet evaluation. As can been seen, the predicted operating vacuum (manometer reading on extraction pipe) of each system was in good agreement with diagnostic predcitions. The predictions on flowrate and negative pressure field extension varied, and was best for the Middle Street Duplex. The results were not as good for the two separate systems installed in the West Street Duplex, though this is likely due to the very tight soils and the overlapping pressure field extensions between the two systems (note: most radon SSD systems operate at flowates between 40 and 100 CFM). Moreover, the sealing of cracks and voild spaces in all buildings occurred after conducting the diagnotic testing, which would lead to lower extraction volumes, as was generally the case.



Resistance and Radon Fan Curves	
Solid Purple Line = Sub-Slab Resistance	Solid Black Line = Fan #1
Solid Red Line = Total System Resistance with 4" Piping	Solid Orange Line = Fan #2
Solid Green Line = Total System Resistance with 3" Piping	Solid Blue Line = Fan #3
Fan Watt lines: Small dash Black =Fan 1; Small dash Orange = Fan 2; Small Dash Blue = Fan 3	

Sub-slab Vacuum - inches of w.c.	**Candidate Fan Models**	**Fan #1**	**Radonaway GP-501**
Large Dash Red Line = Far-Field Ext Pt 1		Fan #2	
Large Dash Black Line = Far-Field Ext Pt 2		Fan #3	

Figure 30 – Spreadsheet Output for Middle Street Duplex with One Candidate Fan

Table 2 - Predicted vs. Actual SSDS Conditions

System	Flowrate (CFM)			Operating Vacuum (in w.c.)			Far-Field Probe		
	Predicted	Actual	% Diff	Predicted	Actual	%Diff	Predicted	Actual	%Diff
West St Duplex 1	32	9	72	-3.6	-3.8	-6	-0.008	-0.01	-25
West St Duplex 2	26	13	50	-3.7	-3.9	-5	-0.025	-0.015	40
Chapel St	26	16	38	-3.7	-3.9	-5	-0.01	-0.012	-20
Chapel St Aptmt	22	26	-18	-3.7	-3.4	8	0.000	0.000	0
Middle St Duplex	44	38	14	-3.3	-2.9	12	-0.025	-0.02	20

On the basis of these efforts, it is concluded that conducting the sub-slab communmication diagnostic testing, as recommended by EPA, is a prudent step to optimize the design of system components, minimize long-term (electricty) costs, and minimize the probability that system performance will be inadedquate, either initially following system activation, or months later.

SSD System Operations

The five SSD Systems at the Newton site were activated in November 2015. Similar to Soil Vapor Extraction systems, the initial discharge concentrations of sub-slab contaminants (and mass flux emissions) exhibited an initial sharp decline, heading toward an asymptotic steady/state condition where contaminant removal rates are controlled by diffusion of VOCs from deeper in the Vadose zone (Figures 31).

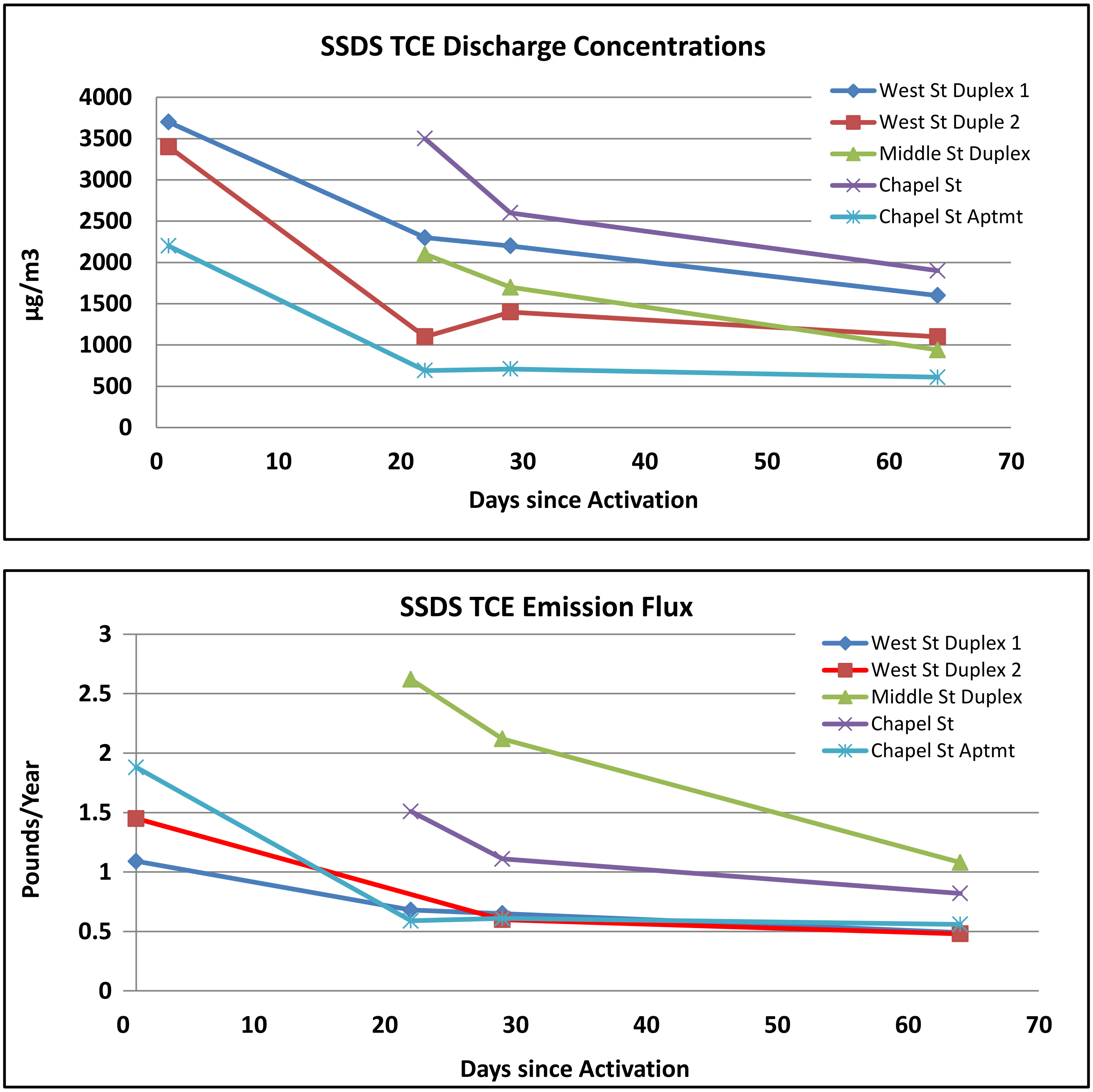


Figure 31 – SSD System TCE Concentrations and Emission Fluxes

Also of interest are the changes in pressure/flows that may occur once a system is activated, due to a number of factors, including the “drying” of sub-slab fill materials, as, in addition to VOCs, water vapor will also be extracted from the subsurface. A diminution in soil pore moisture content could lead to higher flowrates.

Data from the Newton systems for flow and near and far-field sub-slab probe data are presented in Figure 32.

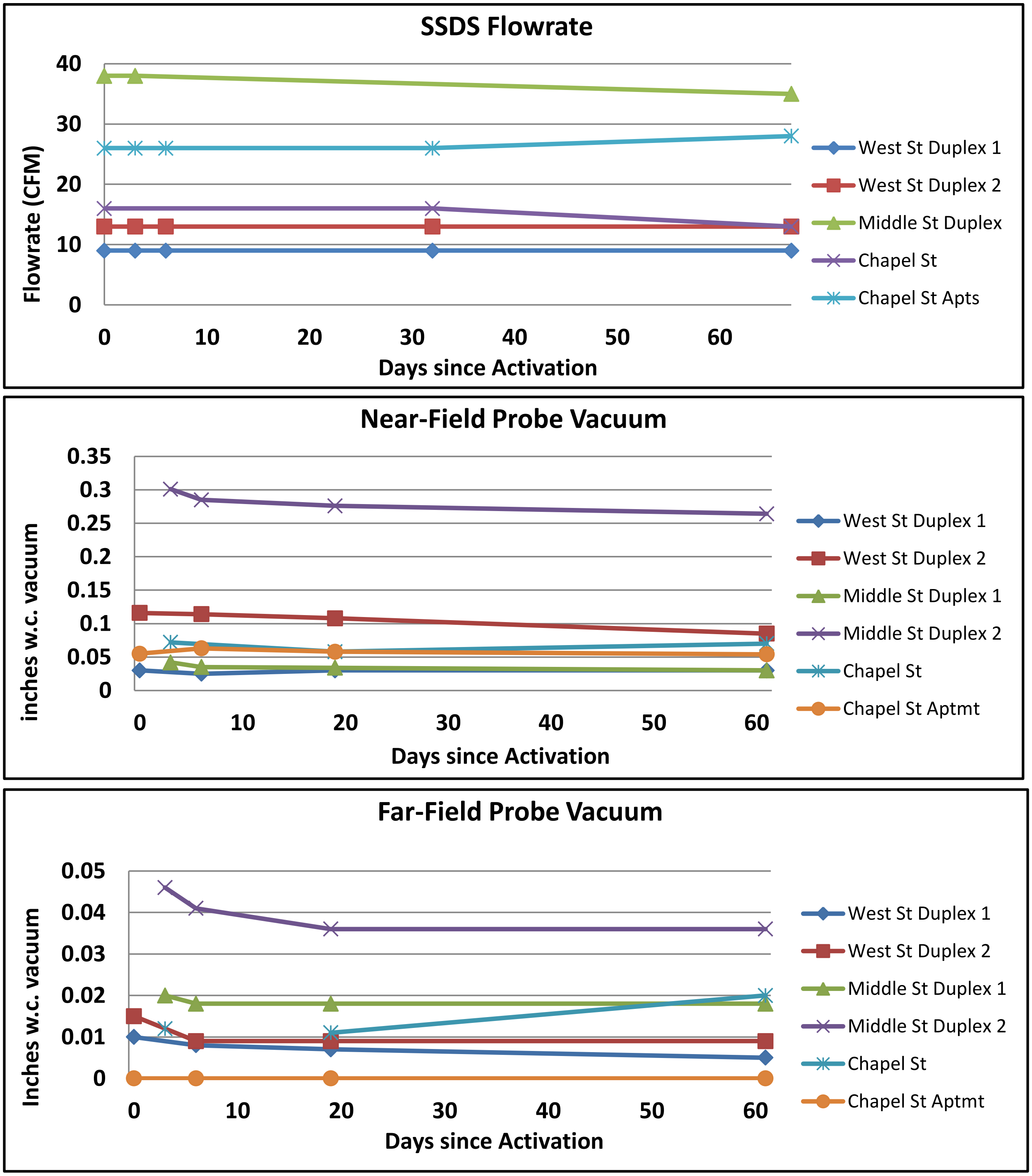


Figure 32 – SSD System Flowrates and Sub-Slab Probe Vacuums

As can be seen, the flowrates remain relatively constant over the first 60 days of operation, as did the measured negative pressure in the near field (about 5 feet from extraction point) and far-field (10 to 30 feet from extraction point) sub-slab probes, with the exception of the far-field probe in the single-family home on Chapel Street. The reasons for the change in the Chapel Street home are not clear. The lack of any discernible "drying effect" may be related to the fact that groundwater was 5 to 10 feet (or more) below the slab elevation in all structures, suggesting that a low moisture-condition may have already been present in the sub slab fill materials even prior to activation of the SSD systems.

Of note is the zero inches w.c. of negative pressure in the far-field probe in the Chapel Street apartment building. The owner of this building did not give permission to install a second extraction point ("leg") in this structure, even though pre-installation diagnostic testing had indicated that the negative pressure field would not extend to the far-field point with a single extraction point. However, this was the building that is detailed in Figure 5, where discrete TCE seeps were noted at the interface of support columns and laminate flooring, and all such voids were sealed with low-VOC caulking prior to activation of the SSD system. It would appear that such mitigate measures, combined with the limited pressure field extension, was sufficient to reduce indoor air TCE concentrations to target levels.

SSD System Effectiveness

The "bottom line" performance standard for SSD systems is the reduction of indoor air concentrations of VOCs to acceptable levels. At this site, that metric was 6 µg/m^3 of TCE (its Imminent Hazard concentration), with a goal to achieve non-detectable concentrations (i.e., < 1 µg/m^3).

At the Newton site, Air-Purifying Units (APUs) were already in operation in all of the impacted structures where SSD systems were installed. The APUs continued to be operated for about 3 weeks after the SSD systems were activated, in order to allow for a transition period for the SSD systems to become fully effective. At this 3 week period, TCE had been reduced to less than 6 µg/m^3 in all homes. A week later, all homes were less than 1 µg/m^3, with the exception of the basement apartment on Chapel Street, which TCE continued to be present in the range of 1 to 3 µg/m^3 (this is the building where the owner would not allow a second extraction point).

A summary of TCE sampling data from key dates in this project is summarized in Table 3.

Table 3 – TCE indoor Air (Grab Sample) Concentrations (µg/m^3)

Date/Milestone	**West St Duplex**				**Chapel St**		**Chapel St**	**Middle St Duplex**			
	Unit 1		**Unit 2**		**Home**		**Apartments**	**Unit 1**		**Unit 2**	
	Basement	**1st Floor**	**Basement**	**1st Floor**	**Basement**	**1st Floor**	**Basement**	**Basement**	**1st Floor**	**Basement**	**1st Floor**
Nov/Dec 2014 (no APU/ SSDS)	**180**	**41**	**76**	**59**	**140**	**16**	**120**	**58**	**28**	**9**	5
Feb/Mar 2015 (APUs)	**24**	2.4	**16**	**7.5**	**10**	<1	**11**	14	<1	NA	1.2
12/8/15 (3 weeks SSDS + APUs)	4.3	<1	1.7	1.8	<1	<1	1.4	<1	<1	<1	<1
12/15/15 (APUs shut down)	<1	<1	<1	<1	<1	<1	1.3	<1	<1	<1	<1
1/19/16 (1 month SSDS only)	<1	<1	<1	<1	<1	<1	2.9	<1	<1	<1	<1

REFERENCES

Austin Air, email and telephone communications with Michael Damon, Vice President of Sales, Buffalo, NY, 2015

Karanfil, T., and Dastgheib, S., *Trichloroethylene Adsorption by Fibrous and Granular Activated Carbons: Aqueous Phase, Gas Phase, and Water Vapor Adsorption Studies*, ES&T, Vol 38, No. 22, 2004

Vizhemehr, Ali Khazraei, *Predicting the Performance of Activated Carbon Filters at Low Concentrations Using Accelerated Test Data*, Ph.D Thesis, Concordia University, Montreal, Quebec, August 2014

Shepherd, A., Technical Director, Carbtrol Corporation, *Activated Carbon Adsorption for Treatment of VOC Emissions*, 2001,

Yao, M. et al., *Investigation of the Treatability of the Primary Indoor Air Volatile Organic Compounds on Activated Carbon Fiber Cloths at Typical Indoor Concentrations*, Journal of the Air & Waste Management Association, 59:7, 882-890, 2009