Pilot Test, Design, and Operation of a Vapor Mitigation System for the Removal of PCE-Impacted Vapors beneath Former Dry Cleaner Site

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ABSTRACT: Environmental investigations at a former dry cleaning facility showed tetrachloroethylene (PCE) in sub-slab soil vapor at two locations at 732 and 5,510 µg/m^3, and trichloroethylene (TCE) at 3.6 and 23 µg/m^3. The building owner retained a consultant who recommended installing a sub-slab vapor mitigation system (VMS) using a ¼ hp radon fan. The building owner solicited a second opinion from Terracon, which recommended a pilot study to collect building-specific data to support the design of the system. Convinced of this logic, the building owner retained Terracon to conduct a pilot test. Based on the results of the pilot test, a full-scale VMS was designed and installed with a 5 hp vacuum blower. Monitoring data show that the VMS has extracted vapors from beneath the slab to achieve non-detectable concentrations of PCE and TCE which resulted in a No Further Action letter from the state regulatory agency. This demonstrates the importance of conducting a pilot test for data to support the design rationale for a VMS that can effectively remove the vapors of concern.

INTRODUCTION

Vapor intrusion is the migration of volatile organic compounds (VOCs) from contaminated groundwater and/or soil into above buildings. To reduce the risk of exposure to these vapors and their associated adverse health effects, a VMS can be installed to vent the vapors in the soil below the building to the exterior of the building. A VMS can be constructed as passive or active. A passive VMS consists of slotted or perforated piping below the ground floor slab or basement floor slab connected to a riser pipe that conveys the vapors to the roof of the building for discharge to the building exterior. An active VMS uses similar components as well as a vacuum blower to mechanically extract vapors from the void space in soil/gravel beneath the slab. To select a vacuum blower that will be effective in creating a sub-slab vacuum to extract the VOCs of concern from beneath the slab, data from a pilot test are needed to determine the blower flow rate and vacuum necessary to create the radius of vacuum influence (ROI) to vent the impacted area in question beneath the slab. The following presents background, methods and materials, results, pilot test data, how results were used for the full-scale design, and system operation of a VMS at a former dry cleaning facility in Denver, Colorado.

BACKGROUND

The subject building is one story with dimensions of 270 ft (82 m) by 200 ft (61 m). A dry cleaning business in Unit B (Figure 1) of the subject building operated from 1998 to 2014, at which time the dry cleaning machine was removed. A Phase I Environmental Site Assessment (ESA) was conducted in 2016 and recommended the collection and analysis of sub-slab vapor samples. Sub-slab soil gas samples were collected at SSVS-1 and

SSVS-2 (Figure 1), analyzed using Method TO-15, and showed PCE and TCE in sub-slab soil gas at SSVS-1 and SSVS-2, 70 feet and 25 feet, respectively, from the former dry cleaning machine. The concentration of PCE in the soil gas at SSVS-1 and SSVS-2 was 732 and 5,510 µg/m^3, and TCE was 3.6 and 23 µg/m^3, respectively. PCE at 5,510 µg/m^3 exceeds the Environmental Protection Agency (EPA) commercial target sub-slab soil gas vapor intrusion screening level (VISL) concentration of 1,600 µg/m^3. TCE was less than its respective VISL of 100 µg/m^3. The data were used to estimate the concentrations at the former location of the dry cleaning machine and then used to estimate sub-slab vapor concentrations isopleths shown in Figure1.

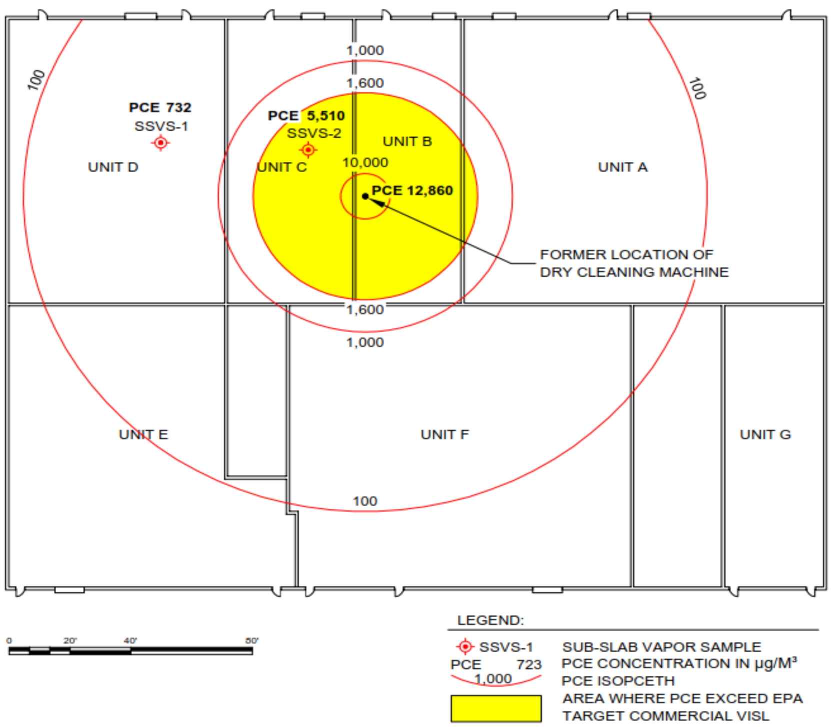


FIGURE 1. Subject Building: Location of SSVS-1 and SSVS-2, and Sub-Slab PCE Concentration Isopleths Soil Gas PCE Concentrations.

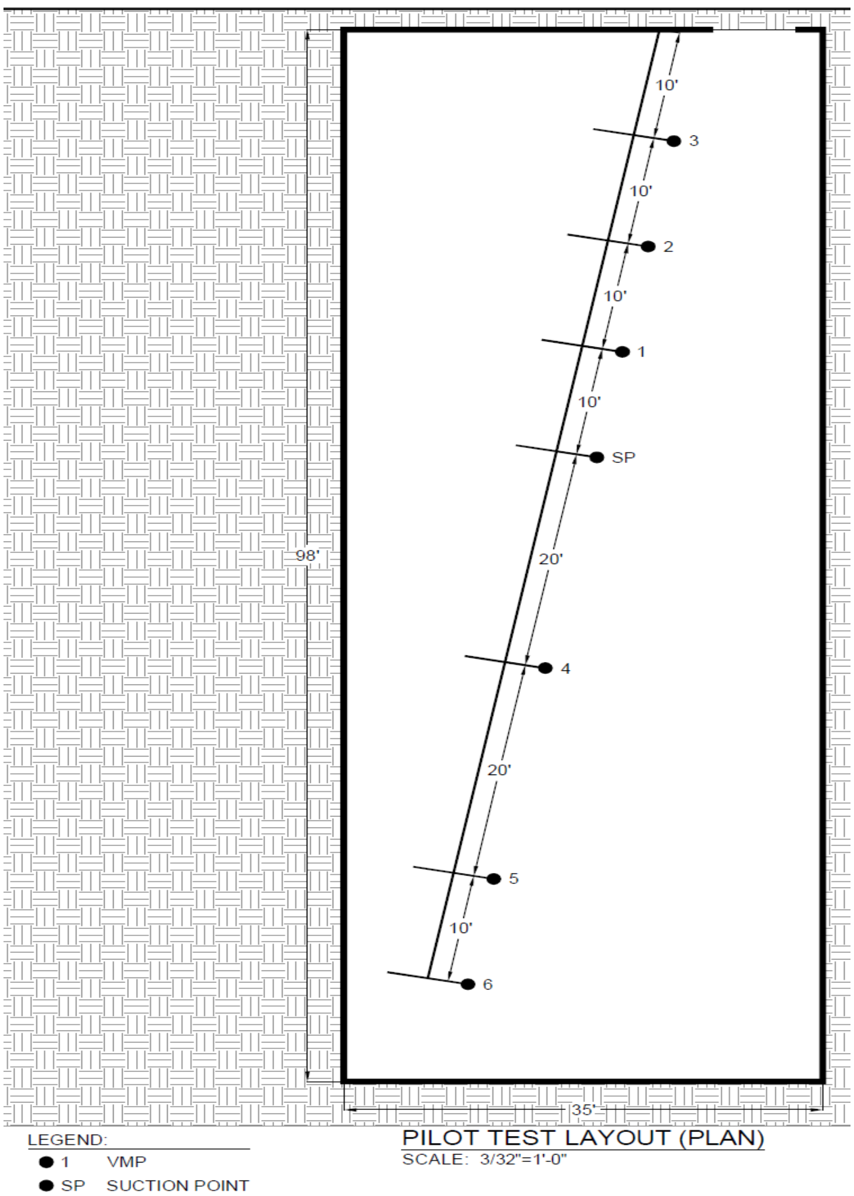
To evaluate if vapors migrated to other units, sub-slab vapor samples were collected in Unit A at SSVS-3 and SSVS-4 (60 ft [18 m] and 120 ft [36 m], respectively, from the former dry cleaning machine) and analyzed for PCE and TCE. The concentration of PCE in the sub-slab vapors was 151 and 247 µg/m^3, respectively, which are less than EPA's target sub-slab VISL of 1600 µg/m^3. TCE was not detected (ND).

Based on the results, the building owner was advised by an environmental consultant to install a VMS with a ¼ hp, 60 cfm (1.7 m^3/min) radon fan and an inlet vacuum of 2 inches (5.1 cm) of water to mitigate the PCE/TCE vapors beneath the slab. The building owner contacted Terracon and requested a second opinion. Terracon recommended that a pilot test be conducted to collect information for sizing the equipment needed to effectively address the sub-slab vapors in the area of concern. Based on this recommendation, the building owner retained Terracon to design the VMS. To develop VMS design parameters, Terracon conducted a pilot test in Unit B where the former dry cleaning machine was located.

MATERIALS AND METHODS

The pilot test used one vapor extraction point (VEP) and six sub-slab vacuum monitoring points (VMPs); three VMPs 10, 20, and 30 ft (3, 6, and 9.1 m) from the VEP, and three VMPs 20, 40, and 50 ft (6, 12.1, and 15.2 m) from the VEP, aligned 180 degrees from the VMPs on the other side of the VEP (Figure 2).

Figure 2. Pilot Test Layout



The VEP was a 1-inch (2.5 cm) diameter steel pipe installed through the 6-inch (15.2 cm) thick concrete floor slab, and connected via a flexible hose to the inlet of a 1.5 hp vacuum blower. A pilot test monitoring unit was used for the test and included 2-inch (5.1 cm) PVC pipe placed between the VEP and the vacuum blower fitted with a 2-inch) 5.1 cm) ball valve, 1-inch (2.54 cm) dilution inlet air valve, vacuum monitoring port, and flow monitoring port. The pilot test unit is shown in Figure 3.

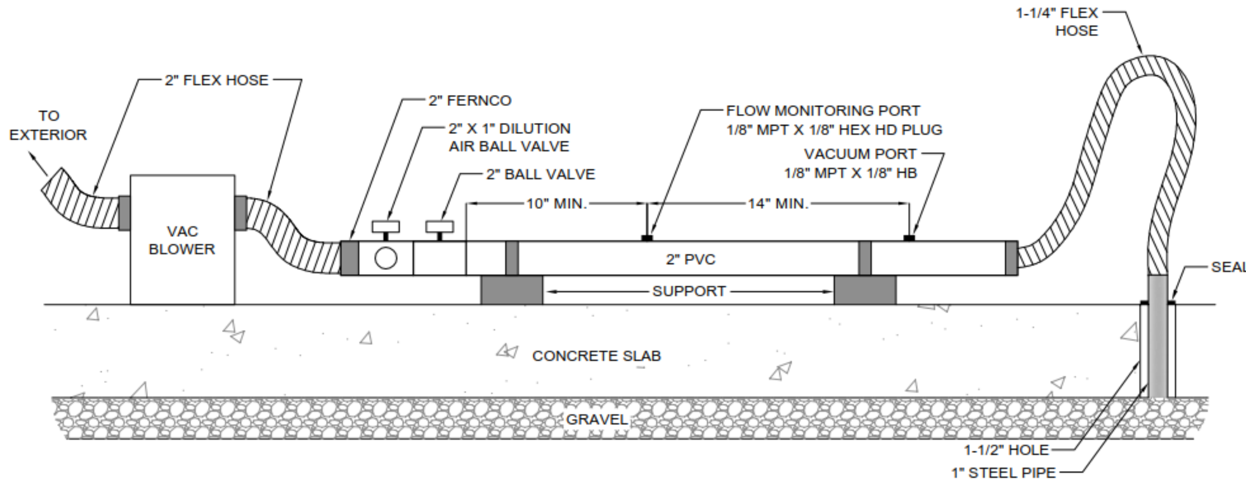


Figure 3. Pilot Test Monitoring Unit

To conduct the test, the ball valve was throttled at 1/3 open, 2/3 open, and full open to create three separate vacuums and flow rates. At each vacuum/flow, the following monitoring (equipment used) was conducted:

- VEP vacuum (digital vacuum gauge with vacuum method detection limit [MDL] of 0.01 inch [0.025 cm] of water)
- VEP flow (vapor velocity anemometer)
- Sub-slab vacuum at the VMPs (digital vacuum gauge with vacuum MDL of 0.001 inch of water [0.0025 cm])
- VOCs in extracted vapors (photoionization detector [PID] with MDL of 1 ppbv) at the outlet of 4-inch (10.2 cm) flexible hose used to convey the extracted vapors from the outlet of the blower 50 ft (15.2 m) to the exterior of the building.

To ensure that the extracted vapors were not explosive, at the beginning of the test the 2-inch (5.1 cm) ball valve was closed then opened slowly, and the bleed air valve was fully open while monitoring the lower explosive limit (LEL) of the extracted vapors. Once the 2-inch (5.1 cm) ball valve was fully open, the dilution air valve was incrementally closed while monitoring the LEL to ensure non-explosive vapors. The pilot test data are shown in Table 1. After conducting the test at three flow rates, a sample of the sub-slab vapors extracted by the vacuum blower was collected using a summa canister. Vapors were analyzed using EPA Method TO-15.

Table 1. Piot Test Data

	DISTANCE	FLOW (CFM) [m3/min]		
	(FT) [m]	95	135	132
		VACUUM (inch water) [cm]		
BLOWER	0	46 [117]	48 [122]	48 [122]
VMP-1	10 [3]	0.48[1.2]	0.512 [1.3]	0.516 [1.3]
VMP-2	20[6.1]	0.058[0.14]	0.065 [0.17]	0.065 [0.17]
VMP-3	30 [9.1]	0.03[0.08]	0.024 [0.66]	0.024 [0.66]
BLOWER	0	46 [117]	48 [122]	48 [122]
VMP-4	20[6.1]	0.084 [0.21]	0.076 [0.19]	0.077 [0.2]
VMP-5	40 [12.2]	0.016[0.04]	0.008 [0.02]	0.005 [0.013]
VMP-6	50 [15.2]	0.011 [0.03]	0.003 [0.008]	0.005 [0.013]
VOCs (ppm)		ND	ND	ND
LEL (%)		0	0	0

RESULTS

Vacuum and Flow Rate. The vacuum on the VEP was 46, 48, and 48 inches (117, 122, 122 cm) of water for tests 1 (1/3 open), 2 (2/3 open), and 3 (full open), respectively. The resultant flow rates of the extracted vapors were 95, 135, and 132 cfm (2.7, 3.8, and 3.7 m^3/min) for tests 1, 2, and 3, respectively.

Sub-Slab Vacuum. In general, sub-slab vacuum decreased with distance away from the suction point in each direction. For VMPs 1,2, and 3, the vacuum decreased up to three orders of magnitude with distance from the VEP. For VMPs 4, 5, and 6, the vacuum decreased up to four orders of magnitude with distance from the suction point. To estimate the radius of influence (ROI), only the data for 95 and 135 cfm (2.7 and 3.8 m^3/min) were used. At each operating condition, graphs showing sub-slab vacuum versus distance were prepared and used a vacuum of 4 Pascals to estimate the ROI. This criterion was used since this is the lower limit of sub-slab vacuum that shall be applied per the EPA (EPA, 2008). The graphs are shown in Figures 4 and 5. The ROI using VMPs 1, 2, and 3 is estimated at 33 ft (10 m) for both 95 and 135 cfm (2.7 and 3.8 m^3/min). The ROI using VMPs 4, 5, and 6 is estimated at 42 ft (12.7 m) at 95 cfm (2.7 m^3/min) and 50 ft (15.2 m) at 135 cfm (3.8 m^3/min), respectively.

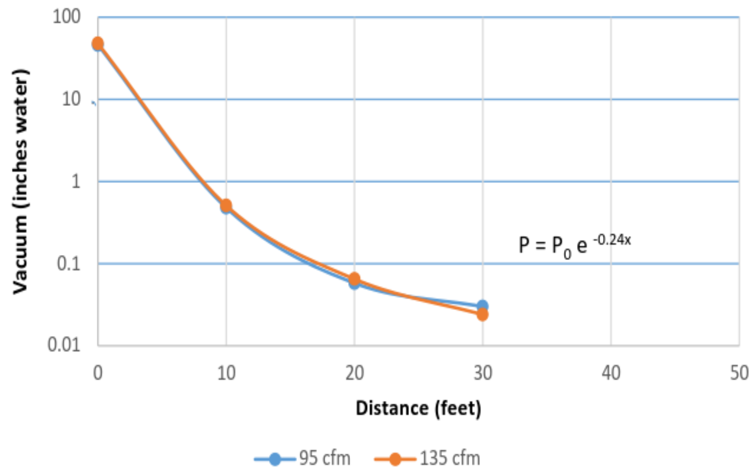


Figure 4. Sub-Slab Vacuum vs. Distance from the VEP for VMP 1,2, and 3

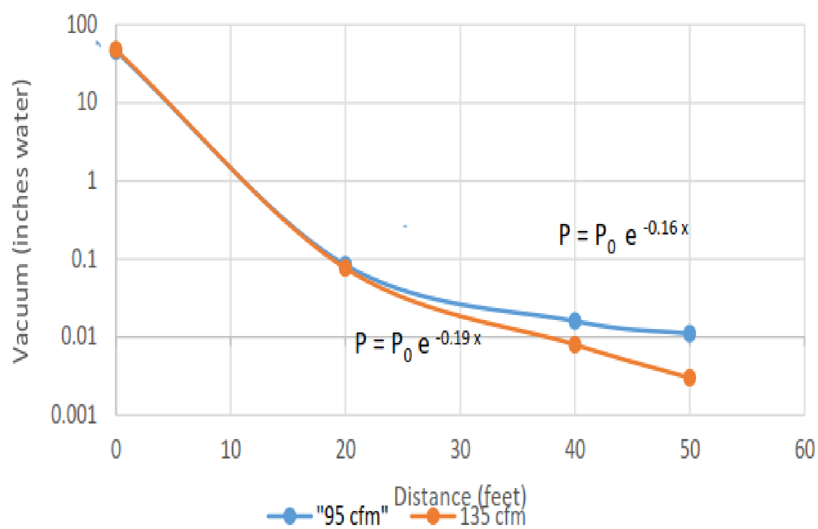


Figure 5. Sub-Slab Vacuum vs. Distance from the VEP for VMP 4,5, and 6

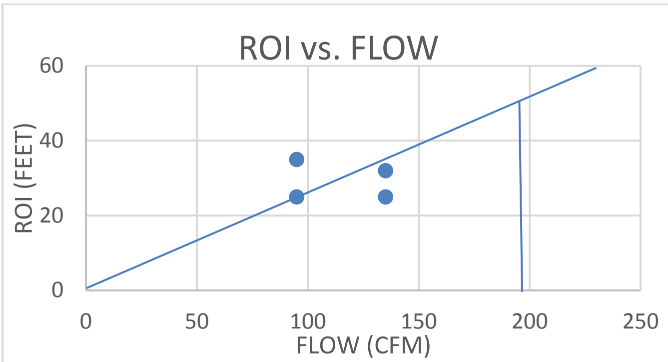
VOCs in Extracted Vapors. VOCs were not detected in the extracted vapors using a PID. However, the results of the TO-15 analyses show a total VOC concentration of 98 µg/m^3 (Table 2). The predominant chlorinated VOCs were PCE and TCE at 48.9 and 5.43 µg/m^3, respectively. These concentrations are less than their respective EPA target sub-slab soil gas VISLs. The presence of PCE and TCE was anticipated since historical sub-slab vapor sampling/analyses detected PCE and TCE in the sub-slab vapors. Using the highest vapor extraction flow rate of 135 cfm measured during the pilot test, the VOC extraction rate is estimated at 0.5 gram/day.

Table 2. VOCs Detected in Extracted Vapors During Pilot Test and Operation of VMS.

ANALYTE	VISL TARGET SUB-SLAB SOIL GAS	EXTRACTED VAPORS - PILOT TEST	EXTRACTED VAPORS - VMS MONITORING	EXTRACTED VAPORS - START UP SPIKE
		5/16/17	11/10/17	11/27/17
		RESULT	RESULT	RESULT
	(ug/m3)	(ug/m3)	(ug/m3)	(ug/m3)
ACETONE	4,500,000	9.2	59.1	230
ALLYL CHLORIDE	68	ND	ND	ND
BENZENE	52	ND	5.05	4.35
BENZYL CHLORIDE	8	ND	ND	ND
BROMODICHLOROMETHANE	11	ND	ND	ND
BROMOFORM	370	ND	ND	ND
BROMOMETHANE	730	ND	ND	ND
1,3-BUTADIENE	14	ND	ND	ND
CARBON DISULFIDE	10,000	ND	2.93	2.51
CARBON TETRACHLORIDE	68	ND	ND	ND
CHLOROBENZENE	7,300	ND	ND	ND
CHLOROETHANE	NR	ND	ND	1.32
CHLOROFORM	18	ND	ND	ND
CHLOROMETHANE	13,000	0.493	0.997	5.8
2-CHLOROTOLUENE	NR	ND	ND	ND
CYCLOHEXANE	150,000	0.661	8	2.42
CHLORODIBROMOMETHANE	NR	ND	ND	ND
1,2-DIBROMOETHANE	68	ND	ND	ND
1,2-DICHLOROBENZENE	29,000	ND	ND	ND
1,3-DICHLOROBENZENE	NR	ND	ND	ND
1,4-DICHLOROBENZENE	37	ND	ND	ND
1,2-DICHLOROETHANE	16	ND	ND	ND
1,1-DICHLOROETHANE	260	ND	ND	ND
1,1-DICHLOROETHENE	NR	ND	ND	ND
CIS-1,2-DICHLOROETHENE	NR	ND	ND	ND
TRANS-1,2-DICHLOROETHENE	NR	ND	ND	ND
1,2-DICHLOROPROPANE	11	ND	ND	ND
CIS-1,3-DICHLOROPROPENE	100	ND	ND	ND
TRANS-1,3-DICHLOROPROPENE	100	ND	ND	ND
1,4-DIOXANE	82	ND	ND	1.62
ETHANOL	NR	7.35	347	129
ETHYLBENZENE	5	ND	3.09	4.26
4-ETHYLTOLUENE	NR	ND	ND	3.17
TRICHLOROFLUOROMETHANE	NR	2.27	3.31	44.2
DICHLORODIFLUOROMETHANE	NR	0.895	2.25	13.1
1,1,2-TRICHLOROTRIFLUOROETHANE	NR	ND	ND	ND
1,2-DICHLOROTETRAFLUOROETHANE	NR	ND	ND	ND
HEPTANE	NR	0.74	10.1	3.31
HEXACHLORO-1,3-BUTADIENE	56	ND	ND	ND
N-HEXANE	3,100	3.49	15.7	6.59
ISOPROPYLBENZENE	NR	ND	ND	ND
METHYLENE CHLORIDE	41,000	0.401	2.53	2.63
METHYL BUTYL KETONE	NR	ND	ND	34.9
2-BUTANONE (MEK)	730,000	12.8	9.69	70.3
4-METHYL-2-PENTANONE (MIBK)	440,000	ND	ND	37.1
METHYL METHACRYLATE	100,000	ND	2.53	14
METHYL TERT-BUTYL ETHER	1,600	ND	ND	ND
NAPHTHALENE	12	ND	ND	ND
2-PROPANOL	NR	ND	124	56.4
PROPENE	440,000	ND	8.92	34.2
STYRENE	155,000	ND	ND	4.65
1,1,2,2-TETRACHLOROETHANE	7	ND	ND	ND
TETRACHLOROETHENE	1,600	48.9	ND	51.5
TETRAHYDROFURAN	290,000	3.62	ND	4.64
TOLUENE	15	0.609	48	201
1,2,4-TRICHLOROBENZENE	290	ND	ND	ND
1,1,1-TRICHLOROETHANE	730,000	ND	ND	ND
1,1,2-TRICHLOROETHANE	26	ND	ND	ND
TRICHLOROETHENE	100	5.43	ND	ND
1,2,4-TRIMETHYLBENZENE	8,800	ND	5.43	4.04
1,3,5-TRIMETHYLBENZENE	NR	ND	2.67	ND
2,2,4-TRIMETHYLPENTANE	NR	1.41	6.12	2.39
VINYL CHLORIDE	93	ND	ND	ND
VINYL BROMIDE	13	ND	ND	ND
VINYL ACETATE	29,000	ND	ND	ND
M&P-XYLENE	15,000	ND	9.43	14.5
O-XYLENE	15,000	ND	3.74	5
	TOTAL	98	681	989

Full-Scale VMS Design Using Pilot Test Data. To select a vacuum blower to remediate the area of concern, the use of one VEP was evaluated. Using the dimensions of the area of concern, the vacuum blower would need to create a 50 ft (15.2 m) ROI. To determine the vacuum/flow rate of the blower needed to attain this ROI, a graph of ROI versus flow was prepared using pilot test data (Figure 6) which shows that a flow rate of approximately 195 cfm (5.5 m^3) is needed.

Figure 6. ROI vs. Flow



To select the appropriate blower for this application, the flow rate of 195 cfm (5.5 m^3/min) at a vacuum of 48 inches (122 cm) of water was adjusted to standard conditions in order to use blower curves for selection of a blower. Based on these criteria and blower curves, a 5 hp regenerative blower was selected for the VMS. Based on the motor/blower required for the full-scale mitigation, a list of equipment and instrumentation for the VMS system included equipment skid with blower/motor, inlet air filter, dilution inlet air valve and filter, vacuum relief valve, inlet vacuum gauge, and vibration isolation pads on bottom of equipment skid (since skid will be mounted on roof).

Emission Controls and Air Permitting. To evaluate if an air permit is needed for the full-scale VMS and if a control technology is needed to reduce VOC emissions, the VOC extraction rate (VOCER) was estimated using the design flow rate of 195 cfm and a VOC concentration of 98 µg/m^3. The estimated VOCER is 0.7 g/day. Assuming continuous (24 hr/7 day/wk /365 day/yr) operation, the maximum discharge of VOCs is estimated at 0.005 lb/yr (0.0022 kg/yr). Since the state regulatory agency requires an air permit for VOC emissions greater than 2 tons/yr (1818 kg/yr), neither an air permit nor a vapor control technology are needed.

After completion of the pilot test and blower sizing, the building owner requested Terracon to fast-track a VMS design and work with a contractor to begin immediate construction of a VMS. The VMS was completed and started approximately seven weeks after the pilot test. The VMS was monitored every two weeks. System operating data are shown in Table 3.

Table 3. VMS Monitoring Results

DATE	NOTE	DURATION OF OPERATING PERIOD	SYSTEM OFF	TOTAL OPERATING TIME	BLOWER VACUUM	VAPOR FLOW RATE	TOTAL VOCS IN EXTRACTED VAPORS	PCE/TCE IN EXTRACTED VAPORS	PCE/TCE EXTRACTION RATE DURING PERIOD	MASS OF PCE/TCE EXTRACTED DURING PERIOD
		(DAYS)	(DAYS)	(DAYS)	(INCHES WATER) [CM]	(CFM) [M3/MIN]	UG/M3	UG/M3	(GRAM/DAY)	(GRAM)
10/11/2017	START	0		0	77 [196]	82 [2.3]	98	54	0.18	0
10/25/2017		14		14	77 [196]	82 [2.3]	NI	NI	0.18	2.53
11/10/2017		16		30	68 [173]	150 [4.2]	681	0	0	2.71
11/20/2017	SHUT OFF	10		40	68 [173]	150 [4.2]	NI	0	0	0
11/27/2017	STARTUP	7	7	40	68 [173]	150 [4.2]	989	52	0.16	3.18
12/12/2017	SHUT OFF	15		55	68 [173]	150 [4.2]	NI	0	0.16	8.75

NOTE:
PCE/TCE CONCENTRATION ON 10/11/17 BASED ON PILOT TEST 8/16/17
NI = NO INFORMATION (ND WITH PID)

Sampling and analyses of the extracted vapors with a PID at the outlet of the blower on October 25, 2017 showed that the concentration of VOCs in the vapors was non-detectable (ND) using a MDL of 1 ppb. Sampling and analyzing the extracted vapors with a PID on November 10, 2017 also showed that the concentration of VOCs in the vapors was ND, so a vapor sample was collected with a 1-L summa canister and the vapors were analyzed using Method TO-15. The analyses showed that although VOCs were detected, PCE and TCE were ND. The results were shared with personnel at the state regulatory agency who suggested that the system be shut off and restarted one week later to check for a startup spike. The VMS was subsequently shut off on November 20, 2017 and restarted on November 27, 2017. After start up, a sample of the extracted vapors was collected with a 1-liter summa canister and analyzed using Method TO-15. Comparing the concentrations of VOCs in the sub-slab soil gas extracted by the VMS to the EPA VISLs, showed that PCE was 52 µg/m^3 which is two orders of magnitude less than its VISL of 1600 µg/m^3, and TCE was ND. Although other VOCs were detected, their concentrations were less than their respective target sub-slab VISLs (Table 2). Terracon shared the results with the state regulatory agency and requested no further action (NFA) at this site. The agency concurred and issued an NFA Approval letter to the building owner.

DISCUSSION

VOCs Detected. Table 2 shows that VOCs other than PCE/TCE (dry cleaning compounds of concern) were extracted from beneath the floor slab. Additionally, the concentrations of these other VOCs increased over time which suggests that vapor phase VOCs not in the immediate vicinity of the VEP but beneath adjacent units continue to migrate toward the VEP suction pit. Although the concentration of these other VOCs increased over time, the concentration never exceeded the EPA VISLs. The other VOCs included petroleum hydrocarbons, clorofluoromethanes/ethanes, and ketones. These VOCs and their detection could be partly explained as follows:

- Petroleum hydrocarbons included BTEX, N-hexane, heptane, and 4-ethyl toluene, all of which VOCs associated with gasoline and not dry cleaning fluids. The presence of these VOCs is possibly due to incidental leakage or spillage of fuel from equipment used during the construction of the building or from use by occupants in adjacent units.
- Trichlorofluoromethane, dichlorodifluoromethane, 1,1,2- trichlorotrifluoroethane, and 1,2-dichlorotetrafluoroethane are typically used as refrigerants and propellants for floor wax and paints. They are not associated with dry cleaning fluids. The presence of VOCs associated with refrigerants is possibly due to incidental leaks of refrigerants by the adjacent refrigeration repair business. The presence of VOCs associated with paints is possibly due to incidental leaks of paints by the adjacent paint and varnish business and/or the use of paints on the floor.
- Acetone, methyl butyl ketone, 2-butanone, and 4-methy-2-pentanone are common industrial solvents and sometimes used in cleaning fluids. The presence of these VOCs is possibly due to incidental leaks of spot removers used by the former dry cleaning business and/or solvents used by adjacent units.

Estimate of Mass of PCE/TCE from Former Dry Cleaning Machine. Given that VOCs were not detected in soil and groundwater but detected in sub-slab vapors, and 17 grams of PCE/TCE was extracted in the vapor phase by the VMS, it is estimated that approximately 10 milliliters of PCE/TCE could have spilled or leaked from the former dry cleaning machine on to the concrete floor, and migrated to the sub-slab soil via openings, cracks, or joints. Based on this volume, very small amounts of VOCs that migrate beneath a floor slab can have a significant impact on sub-slab soil gas VOC concentrations.

Comparison of Proposed Fan to VMS Blower. If the radon fan proposed by the other consultant with a flow rate of 60 cfm was used, it is estimated that it would need to run for approximately 260 days to extract 11,000,000 ft^3 (311,615 m^3) extracted by the VMS installed from startup to shutoff.

CONCLUSIONS

Based on the above, the following conclusions are made:

- In lieu of using general guidelines for sizing and selecting equipment for active VMSs, it is preferable that VMS designers conduct a pilot test to obtain data which more accurately address site-specific conditions. In this way, many of the variables such as sub-slab soil permeability to vapor flow, slab type, sub-slab foundation structures, and vapor flow pathways can be more accurately accounted for. Pilot test data provide information that can be used to size the vacuum blower needed for a specific area of concern which can provide the most technically effective and cost effective VMS design.

- The operation of a VMS could extract VOCs not associated with a specific area of concern if adjacent units in the same building spilled or leaked solvents with other VOCs. If the vapor phase concentrations of these other VOCs exceed their respective VISLs, sub-slab vapor mitigation could be prolonged by the regulatory agency overseeing the project.
- VOC concentrations in vapors extracted by a VMS can increase with time as vapor phase VOCs not in the immediate vicinity of the VEP but within the ROI of the VEP continue to migrate toward the VEP and/or residual liquid phase VOCs in impacted soil continue to volatilize then migrate toward the suction pit.
- The ROI of a VEP can vary depending on the permeability of vapor flow of the medium beneath the slab.
- A small quantity (10 mls) of PCE dry cleaning fluid that is spilled or leaked onto a concrete floor and migrates to sub-slab soil through cracks, joints, or holes can impact sub-slab vapors up to 120 feet (and possibly greater) from the source.

REFERENCES

United States Environmental Protection Agency, 2008. *Indoor Air Vapor Intrusion Mitigation Approaches. Engineering Issue*. EPA/600/R-08-115.