CONCEPTUAL MODEL

Sewers And Utility Tunnels As Preferential Pathways For Volatile Organic Compound Migration Into Buildings: Risk Factors And Investigation Protocol

ESTCP Project ER-201505

NOVEMBER 2018

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LIST OF ACRONYMS

COC	Chemical of concern
DCE	Dichloroethene
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
ft	Feet
NAPL	Nonaqueous phase liquid
PCE	Tetrachloroethene
TCE	Trichloroethene
µg/m^3	micrograms per cubic meter
USEPA	United States Environmental Protection Agency
VI	Vapor intrusion
VOC	Volatile organic compound

KEY TERMS USED IN THIS DOCUMENT

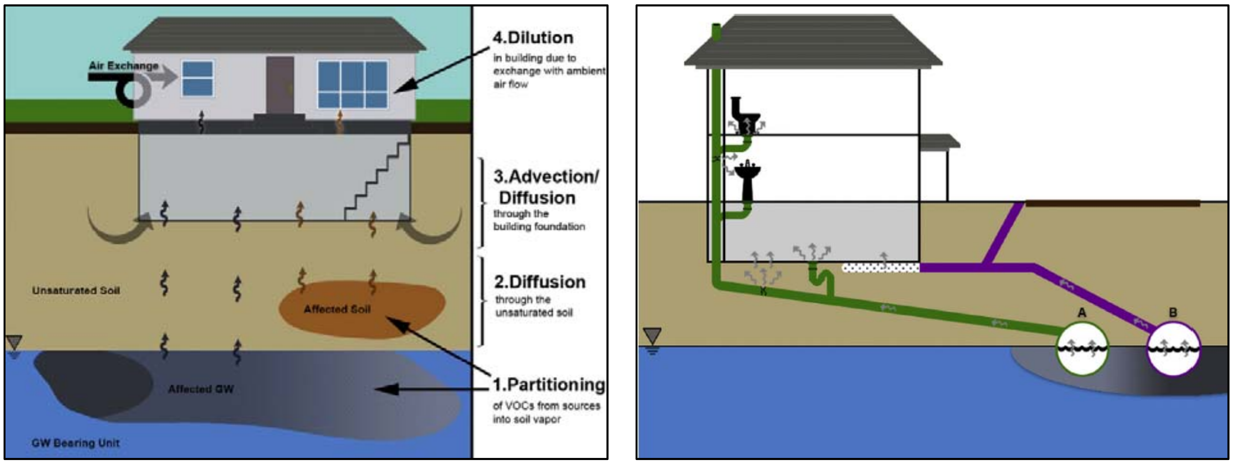
Vapor intrusion	Migration of VOCs from any subsurface source into an overlying building.
Conventional vapor intrusion	Migration of VOCs from a subsurface source into an overlying building by advection and/or diffusion through soil (i.e., not through a preferential pathway). These mechanisms for vapor entry into buildings can also be viewed as "soil gas intrusion." The term "conventional vapor intrusion" used in this document refers to the standard conceptual model that has historically and most commonly been utilized to describe VOC flux from the subsurface into buildings.
Preferential pathway	A migration pathway from a subsurface source that supports higher VOC flux/discharge into a building compared to transport through bulk soil. This general term typically includes features such as elevator shafts and dry wells that can enhance vertical transport from a VOC source below the building into the building and features such as sewers and utility tunnels that can enhance both lateral and vertical transport of VOCs. The term "sewer/utility tunnel vapor intrusion" or "sewer/utility tunnel VI" used in this document refers to VOC flux from the subsurface into buildings though this specific preferential pathway.
Sewer/utility tunnel vapor intrusion (sewer/utility tunnel VI)	A sewer or utility tunnel that supports higher VOC flux/discharge into a building compared to transport through bulk soil. The VOC flux is through the interior of the sewer line or tunnel. Sewer/utility tunnel vapor intrusion has also been referred to as "pipe VI" (Guo et al. 2015). Sewers or utility tunnels can enhance VOC transport into a building from a VOC source that is laterally separated from the building (i.e., not located directly below the building).

Acknowledgements: This research is supported by the U.S. Department of Defense, through ESTCP Project ER-201505. This project would not have been possible without the support and contribution of numerous individuals and organizations. The authors thank project team members Ignacio Rivera-Duarte (Navy Space and Naval Warfare Systems Center Pacific), Steve Hammett and Travis Lewis (NAVFAC EXWC), Dan Groher (USACE), Rich Kapuscinski (USEPA), and Alana Lee (USEPA Region 9). For invaluable project support, we also thank Andrea Leeson and ESTCP program staff at Noblis; the ER-201501 project team including Yuanming Guo and Paul Dahlen (ASU) and Paul Johnson (Colorado School of Mines); Tony Miller and the Entanglement Technologies team; Terry Sullivan (Brookhaven National Laboratory); and Laura Turpen (TestAmerica Laboratories). We are also grateful for the many people involved with demonstration site access and support, including Gary Munekawa, Wilson Doctor, Karen Campbell, and Wes Baumann (Navy); Rob Scofield (GSI); John DeWitt (EKI Environmental); and Chris Lutes (CH2M), Rob Uppencamp (Arcadis) and the USEPA VI Research Duplex team.

1.0 INTRODUCTION

In recent years, a number of sites have been identified with sewer or utility tunnel VI. In many cases, the importance of the sewer or utility tunnel was identified only after extensive site characterization and vapor intrusion testing based on the conventional, or standard, vapor intrusion conceptual model (see Figure 1.1, left panel). We have utilized field investigation results obtained through ESTCP Project ER-201505 along with information compiled from other published and unpublished sources to develop a conceptual model for sewer/utility tunnel vapor intrusion (see Figure 1.1, right panel). Supporting documentation for this conceptual model is provided in the ESTCP Project ER-201505 Final Report (McHugh and Beckley 2018a). The Final Report also includes a recommended protocol for evaluation of sewer/utility tunnel VI as part of vapor intrusion investigations (McHugh and Beckley 2018b).

CONVENTIONAL (STANDARD) VI **SEWER/UTILITY TUNNEL VI**



Note: Figures from McHugh et al. (2017)

Figure 1.1 Conceptual Model for Conventional (Standard) Vapor Intrusion vs. Sewer/Utility Tunnel Vapor Intrusion

Sewer/utility tunnel VI requires:

- A subsurface source of VOCs (i.e., NAPL, soil contamination, or a groundwater plume);
- A sewer line or utility tunnel connecting the subsurface source to a building; and
- A mechanism for VOC entry from the sewer/utility tunnel into the building.

This conceptual model focuses on VOC migration through the interior of sewers and utilities (i.e., inside “pipes” rather than through utility backfill material). The conceptual model also covers: i) typical background concentrations of VOCs in sanitary sewers, ii) variability in VOC concentrations through time, iii) sites with higher risk and lower risk for sewer/utility tunnel vapor intrusion, iv) migration of VOCs within sewers/utility tunnels, and v) VOC migration from sewers and utility tunnels into buildings.

2.0 BACKGROUND VOC CONCENTRATIONS IN SANITARY SEWERS

Because most buildings are connected to sanitary sewers, sanitary sewers are the most common conduit for sewer/utility tunnel VI. In addition to acting as preferential pathways for vapor intrusion, sanitary sewers may contain VOCs from other sources such as the permitted or non-permitted disposal of VOC-containing waste. Typical background concentrations of VOCs in sewers are summarized in Table 2.1.

Table 2.1 Typical Background VOC Concentrations in Sewer Vapor

Analyte	No. Manholes Tested	No. Samples	Det Freq (%)	10th (µg/m^3)	Median (µg/m^3)	90th (µg/m^3)	Maximum (µg/m^3)
Common Chlorinated VOCs at Remediation Sites							
Tetrachloroethene	20	31	90%	0.35	3.2	68	550
Trichloroethene	19	30	70%	0.56	2.6	16	85
Dichloroethene, cis-1,2-	20	31	55%	0.35	0.67	7.5	20
Common Petroleum VOCs at Remediation Sites							
Benzene	55	98	79%	0.32	1.1	4.3	89
Toluene	56	99	98%	1.5	20	280	3300
Ethylbenzene	56	99	74%	0.27	1.4	8.9	190
Xylene, m,p-	57	100	83%	0.82	3.4	21	57
Xylene, o-	58	101	78%	0.34	1.2	4.4	16
Other VOCs							
Acetone	56	99	100%	15	47	200	4000
Bromodichloromethane	58	101	86%	0.44	16	86	540
Butanone, 2- (MEK)	57	100	86%	1.9	4.3	14	66
Carbon disulfide	58	101	99%	3	20	180	940
Carbon tetrachloride	58	101	60%	0.41	0.73	4.4	6
Chloroform	103	249	82%	1	26	360	4000
Chloromethane	58	101	94%	1.1	2	12	100
Dibromochloromethane	58	101	69%	0.67	5.2	33	99
Dichlorodifluoromethane	58	101	77%	1.2	2.3	9.8	38
Methylene Chloride	58	101	97%	0.74	5.1	35	110
Trichlorofluoromethane	58	101	53%	1.1	1.8	11	8.4

Notes: 1) Vapor samples were collected from background manhole locations. 2) Detection frequency was calculated as the number of detected results divided by the total number of samples, multiplied by 100. 3) For the percentile calculations, the detection limit was substituted for non-detects. Percentiles were only calculated if the detection frequency was greater than 10%. 4) See McHugh and Beckley (2018a) for details on the data underlying this table.

As shown in Table 2.1, a number of VOCs are commonly detected in vapor samples collected from sewer manholes not in close proximity (i.e., >200 ft) to known groundwater plumes containing those VOCs. Cis-1,2-DCE, a product of biodegradation of TCE in the subsurface, was detected in 55% of samples suggesting that unidentified subsurface VOC sources are an important source of VOC detections in background sewer manholes. This conclusion relies on an assumption that the cis-1,2-DCE originated from biodegradation of TCE in groundwater rather than biodegradation of TCE within the sewer line. Although this was not directly tested in the ESTCP project, the assumption is reasonable because i) the residence time for TCE within the sewer (i.e., minutes to hours) is likely too short for significant biodegradation and ii) the biodegradation of TCE to cis-1,2-DCE requires anaerobic conditions which are less likely to occur in sewer lines where the flow of shallow water over a rough surface promotes oxygenation.

Other VOCs such as acetone, toluene, and PCE were detected in 90% or more of samples indicating that direct disposal of VOCs into sewers is also an important source of the VOCs detected. For the VOCs that are most commonly risk drivers at corrective action sites (e.g., benzene, PCE, TCE), the concentrations detected in background were typically low (i.e., median <20 $\mu g/m^3$).

3.0 TEMPORAL VARIABILITY IN SEWER VAPOR VOC CONCENTRATIONS

In sewers and utility tunnels, temporal variability in VOC vapor concentrations is relatively high. As shown in Table 3.1, VOC concentrations commonly vary by >10× across quarterly monitoring events. This variability is likely associated with i) variations in VOC entry into the sewer/utility tunnel particularly when it is within the zone of groundwater fluctuation and ii) variations in ventilation associated with wind, temperature gradients, and other ambient factors. Recommendations to address temporal variability (e.g., sampling frequency) are provided in the protocol for evaluation of sewer/utility tunnel VI (McHugh and Beckley 2018b).

Table 3.1 Summary of VOC Concentration Changes over Different Time Scales

No. Locations Tested	Timeframe	Median and Range of Concentration Ratios (Minimum - Maximum)	Median Coefficient of Variation
26 – Sanitary 8 – Land Drain 9 – Combined Storm/Sanitary 6 – Utility Tunnel	1 – 3 days	3.5 (1.1 – 590)	0.59
11 Sanitary Houston, Texas	12 to 18 months	30 (5.2 – 2200)	2.3
16 Sanitary Layton, Utah	12 to 15 months	34 (1.8-750)	3.7
35 Land Drain 2 Storm Sewer Layton, Utah	12 to 15 months	11 (1.3-1300)	1.3

Notes: 1) Concentration Ratios were calculated as the maximum divided by the minimum VOC concentration measured in a given manhole over the course of the test period. 2) Coefficient of variation estimated assuming a log-normal distribution. 3) Laterals were not considered in the evaluation. 4) See McHugh and Beckley (2018a) for details on the data underlying this table.

4.0 HIGHER RISK AND LOWER RISK SITES

There is some sewer/utility tunnel vapor intrusion concern at sites with both i) a subsurface VOC source and ii) sewers or utility tunnels connected to buildings. These sites, however, can be grouped into higher risk and lower risk categories (see Figure 4.1) based on the interaction between the sewer and the VOC source such as contaminated groundwater.

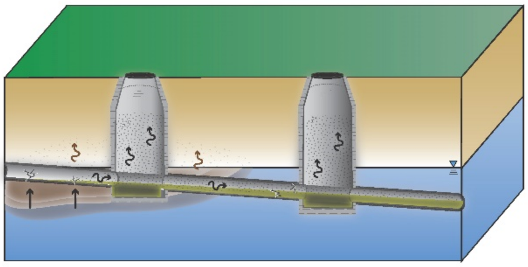
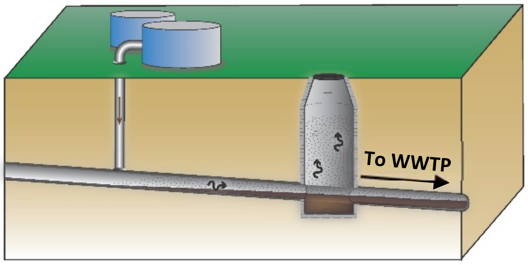
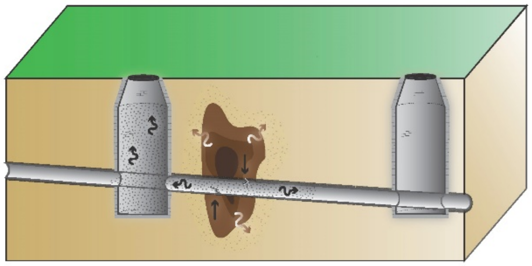
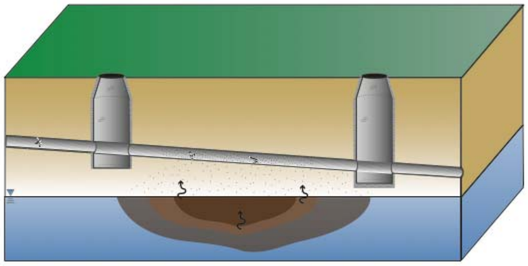
Higher Risk Scenarios	**Lower Risk Scenario**
A: Sewer Intersects Contaminated Groundwater  B: Discharge of Groundwater to Sewer Line  C: Sewer Intersects NAPL/Vadose Zone Source 	Sewer in Vadose Zone above Plume 

Figure 4.1 Higher Risk and Lower Risk Scenarios for Sewer/Utility Tunnel Vapor Intrusion

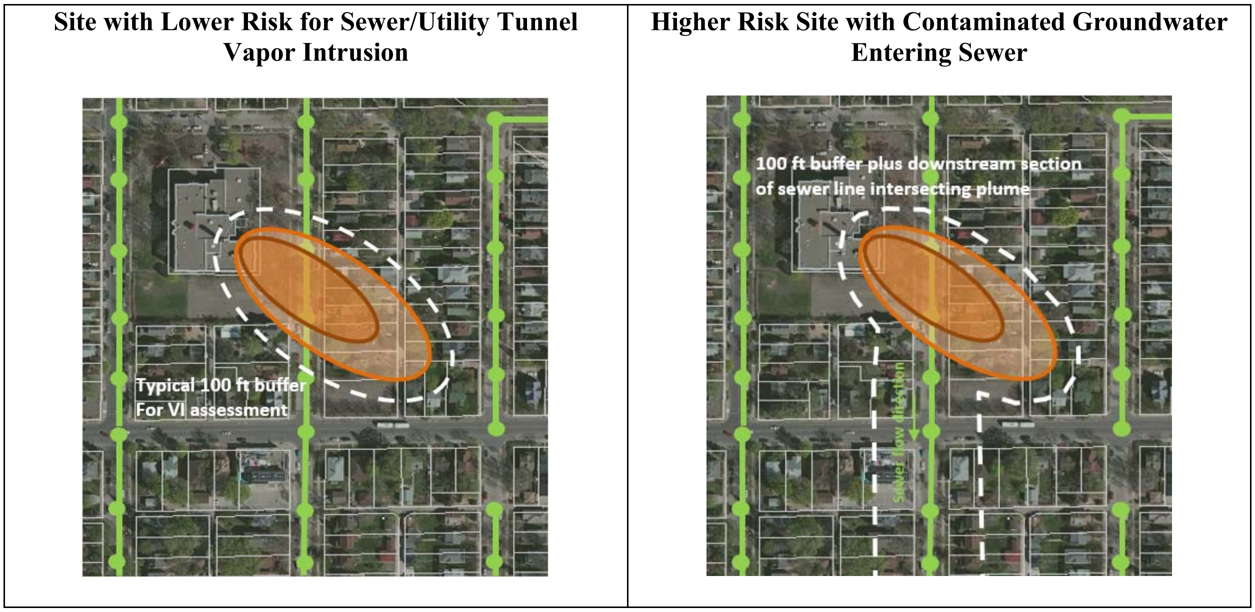
As shown in Figure 4.1, higher risk sites are characterized by direct interaction between the subsurface source and the preferential pathway (e.g., the sewer line or tunnel is below the water table) while lower risk sites are characterized by an indirect interaction between the subsurface source and the preferential pathway (i.e., the sewer or utility tunnel is located in the vadose zone above the groundwater plume or other VOC source). Migration of VOCs from groundwater plumes into the sewer/utility tunnel can occur at both higher risk sites and lower risk sites (see Table 4.1). However, less attenuation of VOC concentrations between groundwater and the sewer vapors was observed at the higher risk sites (i.e., groundwater to sewer attenuation factors were closer to one) compared to the lower risk sites.

Table 4.1 Groundwater to Sewer Attenuation Factors

Site Category	No. Plumes	No. AFs	Attenuation Factor [1]	Attenuation [2]
			Median (10th – 90th percentiles)	Median (10th – 90th percentiles)
A: Direct Interaction (Sewer Below Water Table)	6	65	7.5E-03 (8.4E-05 – 6.5E-02)	130× (12,000× - 15×)
B: Indirect Interaction (Sewer Above Water Table)	28	140	1.4E-04 (2.0E-06 – 5.9E-03)	7,300× (490,000× - 170×)

Notes: 1) Attenuation factor calculated as sewer vapor concentration divided by equilibrium groundwater concentration. 2) Attenuation is the inverse of attenuation factor. 3) See McHugh and Beckley (2018a) for details on the data underlying this table.

For conventional vapor intrusion investigations, focus areas are typically designated as areas above the footprint of subsurface impacts plus a buffer, commonly taken as 100 feet (USEPA 2015), as shown in the left panel of Figure 4.2. At sites where contaminated groundwater enters the sewer (i.e., direct interaction sites), downstream VOC migration in sewer liquid and vapor may result in impacts to buildings located away from the subsurface VOC source (i.e., beyond the 100 ft screening distance commonly used to identify buildings at risk for vapor intrusion (Figure 4.2, right panel).



Site with Lower Risk for Sewer/Utility Tunnel Vapor Intrusion

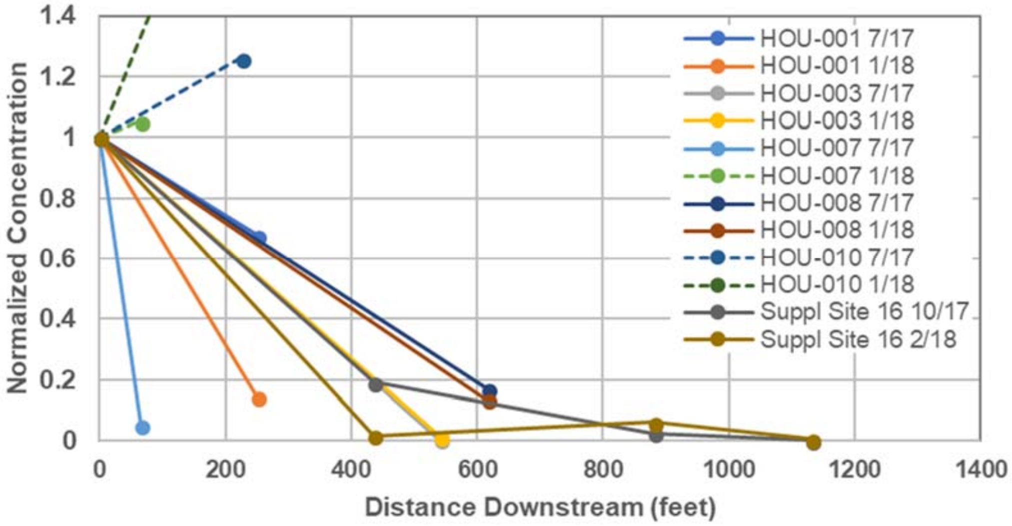
Higher Risk Site with Contaminated Groundwater Entering Sewer

Figure 4.2 Sewer/Utility Tunnel Vapor Intrusion Risk Area

5.0 MIGRATION OF VOCS WITHIN SEWERS

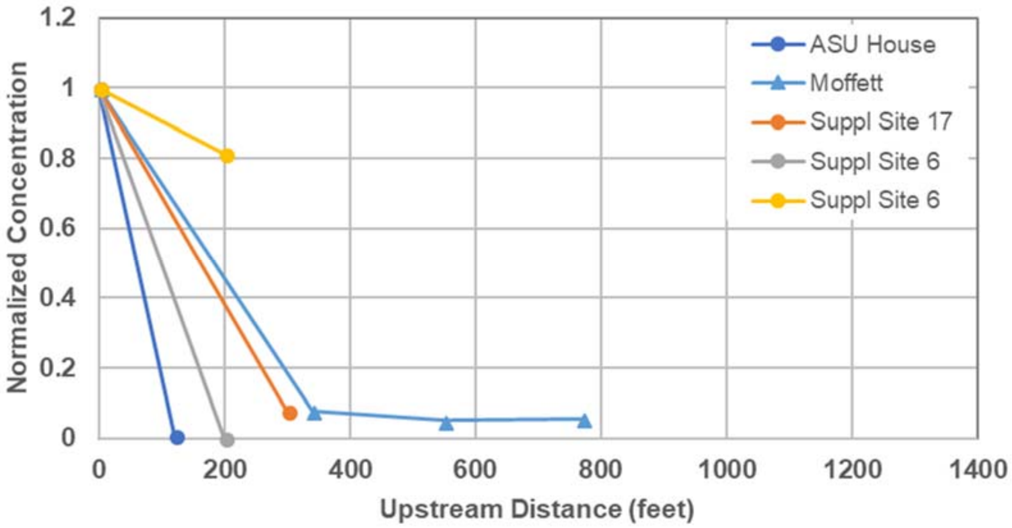
The migration of VOCs within sewer lines depends on whether the VOCs enter the sewer in the liquid phase or the vapor phase. When contaminated groundwater enters a sewer line, it will flow downstream with the liquid flow in the sewer. VOCs partitioning from the liquid phase into the vapor phase can result in vapor impacts for an extended distance downstream of the subsurface source area. In these cases, the extent of downstream impacts will depend on a number of factors and will be difficult to predict; however, it is possible for these downstream impacts to extend well outside the footprint of the VOC plume in groundwater.

VOCs in the sewer vapor phase can result from partitioning from sewer liquids or from direct vapor entry (i.e., contaminated soil gas). Once in the vapor phase, the direction of movement within a sewer or utility tunnel is somewhat less predictable compared to the liquids. If there are liquids in the sewer, these liquids will flow downslope under the influence of gravity. Friction at the liquid surface commonly creates an advective flow of air within the sewer in the direction of liquid flow (i.e., drag). However, transient pressure gradients can drive air flow upstream or through sewer laterals. Regardless of the direction of vapor movement, when VOCs are not present in sewer liquids, the VOC concentrations in the vapor phase will typically decrease quickly with distance away from the subsurface source (see Figures 5.1 and 5.2). This is because sewers and utility tunnels are vented, allowing both dilution of vapors with ambient air and escape of VOC vapors to the atmosphere.



Notes: 1) Chart summarizes results from sewer lines sampled at 2 or more manholes. Manholes over the plumes (i.e., in the source areas) are plotted at 0 ft. 2) Normalized concentrations calculated as manhole concentrations divided by source area manhole concentration. 3) HOU-007 and HOU-010 have limited plume delineation data in the uppermost water bearing unit. 4) See McHugh and Beckley (2018a) for additional information.

Figure 5.1 Normalized Concentration vs. Distance Downstream of Source Area (Vadose Sites)



Notes: 1) Chart summarizes results from sewer lines sampled at 2 or more manholes. Source area manholes are plotted at 0 ft. 2) Normalized concentrations calculated as manhole concentrations divided by source area manhole concentration. 3) See McHugh and Beckley (2018a) for additional information.

Figure 5.2 Normalized Concentration vs. Distance in Upstream Manholes

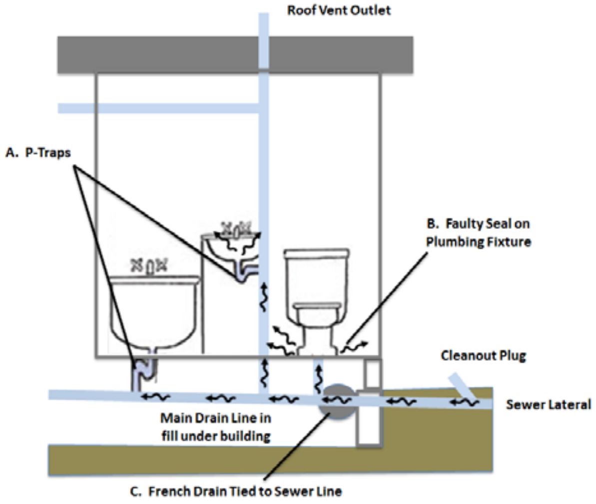
6.0 VOC MIGRATION INTO BUILDINGS

The potential for migration of VOCs from sewers or utility tunnels into buildings depends on the integrity of the connections.

Sanitary Sewer Lines: Because sanitary sewers commonly generate noxious odors, building plumbing systems are engineered to prevent gas flow from the sewer into the building. However, failures in these systems can allow gas entry through a variety of mechanisms (Figure 6.1). In buildings with properly constructed and functioning plumbing, we commonly observe high attenuation in VOC concentrations between the sewer line and the building. However, less attenuation is observed in buildings with plumbing failures.

Utility Tunnels: At DoD facilities and other campuses, telephone lines, electrical lines, and other utilities are commonly connected to buildings through utility tunnels. These tunnel connections often do not include systems to limit gas flow because the tunnels may not be an expected source of noxious odors. As a result, VOC attenuation from utility tunnels into buildings is likely to be low compared to buildings with properly functioning sanitary sewer connections (i.e., less decrease in VOC concentration from the utility tunnel into the building compared to the sanitary sewer into the building).

Other Sewer Lines: Many building foundations have drain systems to prevent the infiltration of shallow groundwater or infiltrating storm water. In some areas, these drain systems are connected to the local storm sewer system (or a separate land drain sewer system). In these cases, VOCs can migrate from the storm sewer line to the building foundation and then migrate through the building foundation via the same mechanisms as with conventional vapor intrusion (for example, see Guo et al. (2015)).



Notes: VOCs can move from sewers and utility tunnels into buildings through a variety of features, for example: A. Dry p-traps; B. Faulty seal on plumbing fixture (e.g., Pennell et al. 2013); and C. French drain tied to sewer line (Guo et al. 2015). Utility tunnels can vent directly into buildings.

Figure 6.1 Potential Entry Points into Buildings

Observed attenuation of VOCs in vapors from sewers into building indoor air is summarized in Table 6.1.

Table 6.1 Sewer to Building VOC Attenuation

Building Types	Range of Attenuation
Buildings with Known Sewer/Utility Tunnel VI Issues	30 – 50×, or greater
Buildings with No Known Issues	2 of 12 buildings: 20× – 50×, or greater 10 of 12 buildings: 100×, or greater

Notes: 1) See McHugh and Beckley (2018a) for details on the data underlying this table.

7.0 OVERVIEW OF SEWER/UTILITY TUNNEL VI MITIGATION

Sewer/utility tunnel VI may be mitigated at any of three steps along the VOC transport route: i) entry of VOCs into the sewer, ii) the sewer main line, or iii) migration of VOCs from the sewer into the building (see Table 7.1).

Entry of VOCs into Sewer or Utility Tunnel: Contaminated groundwater commonly enters a sewer line or utility line through cracks or unsealed joints present in the area where the line passes through the contaminant plume or source area. The infiltration of contaminated groundwater can be reduced or eliminated by installing a plastic liner in the sewer line and manholes within the plume area. Replacement of damaged sewer lines can also be done. Alternatively, sewer lines can be re-routed to avoid the contaminated area.

Ventilation of the Sewer Main or Utility Tunnel: VOC migration from sewers and utility tunnels into buildings can be controlled by negative pressure ventilation of the sewer line. Within the depressurization zone, this will draw vapors from the sewer to the ventilation points allowing for treatment and/or discharge to the atmosphere.

Migration of VOCs from the Sewer into the Building: For some buildings, repair or proper maintenance of the building plumbing (e.g., adding water to a dry p-trap) may be sufficient to prevent VOC migration from the sewer into the building. Alternatively, a check valve (for both liquids and gas) can be installed within the sewer line. A liquid and gas check value allows the flow of liquid down the sewer line but prevents the flow of either liquids or gas upwards. This type of check valve can be installed in the sewer lateral to protect an individual building or within a sewer main line (upstream of the VOC source) to protect all structures upstream of the check valve.

Table 7.1 Examples of Sewer Mitigation Methods Used to Control Vapor Intrusion

Site	Mitigation Method	Reference
#4. Dry Cleaner Site, Denmark	Depressurization of sewer line	Nielsen et al. (2014)
#5. Petroleum Solvent LNAPL, United Kingdom	Replaced collapsed portion of sanitary sewer line and installed an interior liner to prevent infiltration of LNAPL	Macklin et al. (2014)
#6. TCE Plume, Indianapolis, Indiana	Relocated sewer line so that it did not intersect the contaminated groundwater plume	ERM (2017)
#7. Various Sites, Denmark	Paper summarizes several approaches for sewer line mitigation: - Repairing or lining sewer line to prevent infiltration of liquids or vapors - Sealing or repairing leaky/damaged water traps inside of building - Passive ventilation of manholes - Depressurization of sewer system	Nielsen and Hivdberg (2017)
#10. Tranguch Gasoline Site, Pennsylvania	Installed check valves (backflow preventers) in each of 292 sewer lateral lines connecting residences to the sanitary sewer line containing elevated petroleum vapor concentrations. For VI mitigation, the check valve must control both liquid and vapor flow (e.g., Checkmate inline check valve).	Jarvela et al. (2004)
#11. DoD Facility	Sewer line ventilation	Riis et al. (2010) Nielsen and Hivdberg (2017) ERM (2017) Holton and Simms (2018)
#12. TCE Plume, California	Repaired sewer line	Viteri et al. (2018)
#14. Navy Facility, New Jersey	Installed liner (cured in-place pipe (CIPP)) inside sewer line to prevent infiltration of contaminated groundwater	Turco (1996)

Notes: 1) See McHugh and Beckley (2018a) for more information.

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