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## **Evidence of a Sewer Vapor Transport Pathway at the USEPA Vapor Intrusion Research Duplex**

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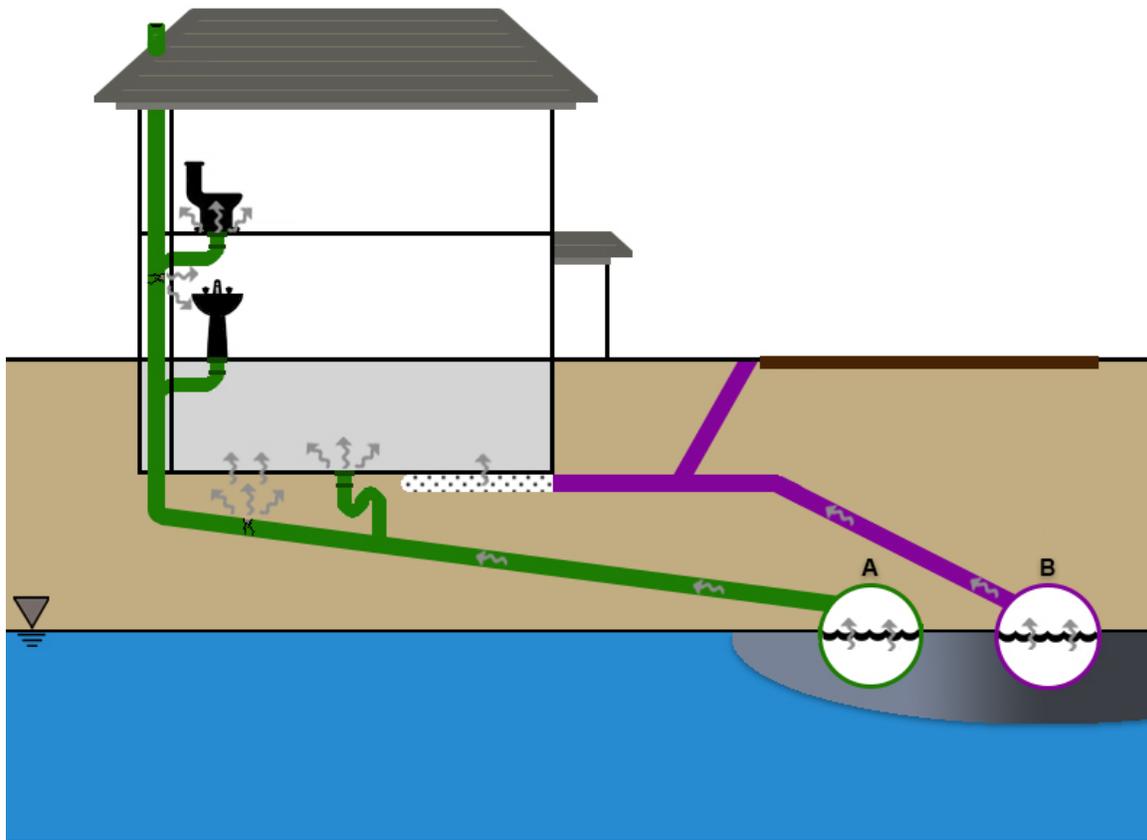
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1 Vapor intrusion is the vapor phase migration of volatile contaminants from a subsurface  
2 source into overlying buildings or other structures. Although vapor intrusion has been  
3 recognized for decades as a potential exposure pathway, the discovery in the late 1990s  
4 of unexpected vapor intrusion exposures at some sites with large groundwater plumes  
5 increased the focus on this pathway beginning in the early 2000s (Tillman and Weaver,  
6 2005). Since that time, field investigations, regulatory guidance, and research efforts  
7 related to vapor intrusion have greatly increased.

8  
9 One key challenge for the evaluation of vapor intrusion is high spatial and temporal  
10 variability in VOC concentrations within shallow groundwater, soil gas, and indoor air  
11 (McHugh et al., 2007). This high variability makes it difficult to evaluate pathway  
12 completeness using conventional field investigation methods. In order to better  
13 understand the effect of spatial and temporal variability in vapor intrusion, Holton et al.,  
14 2013 conducted an intensive multi-year testing program at a single family residence  
15 overlying a chlorinated solvent plume in Utah. They found that trichloroethene (TCE)  
16 concentrations in indoor air varied by 1000x over time. They found extended periods of  
17 no vapor intrusion and shorter periods where vapor intrusion yielded TCE concentrations  
18 well above United States Environmental Protection Agency (USEPA) screening values.  
19 In addition, unexpected patterns in the distribution of TCE below the residence led to the  
20 eventual discovery of a foundation drain system acting as a preferential pathway for TCE  
21 migration into the residence (Guo et al., 2015). At this residence, the sub-foundation  
22 gravel layer is connected to a neighborhood land drain sewer system. This provides a  
23 migration pathway for vapors from the land drain sewer to the sub-slab and then into the  
24 residence through a foundation expansion joint and other penetrations.

25  
26 A preferential pathway is typically defined as a high permeability conduit that can serve  
27 as a high-capacity transport pathway for volatile organic compound (VOC) vapors from  
28 the source area to or into a building. More specifically, the Navy VI Evaluation Tool  
29 (Caldwell 2012) uses the definition: "*Preferential pathways are natural or anthropogenic*  
30 *subsurface features of higher permeability or air filled porosity than the surrounding matrix.*  
31 *Preferential pathways may transport vapors farther or faster than what would be predicted*  
32 *by vapor transport models or assumptions (i.e., the Johnson and Ettinger model or*  
33 *attenuation factors)*" (Caldwell 2012). Some have further defined the term "atypical  
34 preferential pathway" to refer to a building feature that is not commonly found in  
35 association with most structures of the same general class (i.e., single family residences,  
36 office buildings). If sufficiently deep, elevator shafts, dry wells or cisterns can act as  
37 vertical preferential pathways enhancing the transport of VOC vapors into a building from  
38 a groundwater source located below the building. Sewers or utility tunnels can also serve  
39 as preferential pathways for vertical and lateral migration of VOC vapors (Figure 1).  
40 Sewers or utility tunnels are of greatest concern when they pass directly through  
41 contaminated groundwater or vadose zone non-aqueous phase liquid (NAPL) sources  
42 since those locations could provide the highest concentration infiltration into the conduit.  
43 When sewers pass through contaminated groundwater, this groundwater may infiltrate  
44 into the sewer allowing partitioning into the gas phase to occur within the sewer line. In  
45 these cases, vapor intrusion impacts may occur in buildings laterally offset from the  
46 groundwater plume but connected to the sewer line running through the plume (Figure 1).



1  
 2 Figure 1. Conceptual illustration of sewer preferential pathways for vapor intrusion. A)  
 3 Most residences (i.e., those without septic tanks), are connected to the sanitary (or  
 4 combined storm and sanitary) sewer system. B) Some residences have foundation drain  
 5 systems connected to land drain or storm sewer systems. Although prohibited by current  
 6 building codes, some residences may have older or illegal foundation drains connected to  
 7 the sanitary sewer system. Clean-outs and manholes are not shown.

8  
 9  
 10 Storm sewers, sanitary sewers, and utility tunnels have been identified as important  
 11 preferential transport pathways for VOC vapor intrusion at a small but growing number of  
 12 sites. Examples include: vinyl chloride vapor intrusion at a former dry cleaner site (Nielsen,  
 13 et al. 2014), several houses near a tetrachloroethene (PCE) plume in Denmark (Riis, et  
 14 al. 2010), a house at Hill Air Force Base Operable Unit 2 (McHugh, et al. 2011), a Boston  
 15 area house (Pennell, et al. 2013), and a building at Moffett Field, California (McHugh et  
 16 al., 2012).

17  
 18 The USEPA vapor intrusion research duplex is a residence in Indianapolis, Indiana that  
 19 has been intensively studied in order to better understand vapor intrusion processes  
 20 (USEPA, 2012; USEPA, 2015a; USEPA, 2015b; Lutes 2015). Since 2011, a USEPA-  
 21 funded research team has monitored VOC concentrations and other parameters in indoor  
 22 air, soil gas, and groundwater. Similar to the research house in Utah (Holton et al., 2013),  
 23 the USEPA team found large spatial and temporal variations in VOC concentrations in  
 24 indoor air, subslab, and soil gas. Geophysical testing in and around the research duplex  
 25 confirmed the location of many known features and suggested that the concrete basement

1 slab varied in thickness. The basement slab has an irregular contact with the underlying  
2 fill material resulting in air gaps. Helium tracer testing with injection at deep external soil  
3 gas points showed spatial variations in helium concentrations that indicate subsurface  
4 heterogeneity and possible preferential flow paths below the foundation of the research  
5 duplex. Temporal variations in PCE and chloroform within the duplex have been attributed  
6 to several factors including exterior temperatures, heating system usage, barometric  
7 pressure, indoor humidity, and possibly wind effects. Based on differences in the spatial  
8 distribution of PCE vs. chloroform as well as differences in the observed temporal changes  
9 in concentration, the USEPA study team concluded that these two compounds may  
10 originate from different primary sources (e.g., former dry cleaner site vs. water disinfection  
11 by-product; USEPA, 2012). In 2013, a sub-slab depressurization system was installed in  
12 the duplex as part of the research effort. The system was operated intermittently from  
13 2013 to 2015, but has been off since March 20, 2015.

14  
15 Some of the VOC concentration results collected from the USEPA research duplex have  
16 not been consistent with the standard conceptual model for vapor intrusion suggesting the  
17 possibility of a preferential pathway. For example, PCE and chloroform concentrations in  
18 groundwater are generally less than 1.5 ug/L while the concentrations in indoor air have,  
19 at times, exceeded 10 ug/m<sup>3</sup> for PCE, much higher than the 1.2 ug/m<sup>3</sup> upper-bound  
20 concentration predicted using the USEPA 95<sup>th</sup> percentile screening attenuation factor of  
21 0.001 (USEPA, 2015c). In addition, the PCE concentrations in sub-slab soil gas are  
22 sometimes higher than at sample points deeper within the vadose zone suggesting an  
23 absence of upward diffusion from the water table. Finally, early in the study, high  
24 concentrations of PCE and chloroform (each approximately 300 ug/m<sup>3</sup>) were measured in  
25 a floor drain on the first floor of the duplex (USEPA, 2012). Subsequently, all of the floor  
26 drains on the upper floors were plugged to prevent direct entry of sewer vapors into the  
27 duplex. A floor drain in the basement needed for the furnace was not plugged.

28  
29 The purpose of this study was to measure VOC concentrations in the sewer line connected  
30 to the USEPA research duplex and to perform other testing to evaluate the role of a sewer  
31 preferential pathway at this duplex. Aside from one round of floor drain testing in 2011,  
32 VOC concentrations in the duplex sewer system were not measured prior to our field study.

## 33 34 **2.0 Methods**

### 35 36 *2.1 Overview of the testing program.*

37 The field sampling program was conducted from June 12 to June 16, 2016. Vapor  
38 samples were collected from sewer manholes, existing soil gas and sub-slab monitoring  
39 points, the sewer lateral line connecting the duplex to the sewer main, and locations inside  
40 the duplex. Liquid samples were collected from three sewer manholes and two existing  
41 groundwater monitoring wells. The analytical testing program included on-site analysis of  
42 vapor samples, off-site laboratory analysis for vapor and liquid samples, and a tracer study.

### 43 44 *2.2 Vapor sample collection.*

45 Vapor samples were collected from sewer manholes through existing vent holes in the  
46 manhole cover or by moving the cover enough to allow passage of the sampling tube.  
47 Liquid levels were measured using a water level meter. Vapor samples were collected at  
48 a depth of approximately 0.3 m above the liquid level or 0.3 m above the base of the  
49 manhole in cases where the liquid did not cover the base outside of the invert flow channel.  
50 Vapor samples were collected using weighted, 3 mm outside diameter Nylaflow tubing  
51 lowered to the sample collection depth. Prior to sample collection, more than three line

1 volumes of air (approximately 50 mL) were purged from the tubing using a 3-way valve  
 2 and gas-tight syringe. Samples were collected in 1-L Tedlar bags using the 3-way valve  
 3 and gas-tight syringe or in 1-L Summa canisters without flow controllers. Collection of  
 4 vapor samples from the existing soil gas and sub-slab monitoring points involved similar  
 5 procedures for line purging and sample collection. The sewer lateral line was sampled by  
 6 drilling a hole into the PVC sewer lateral pipe in the duplex basement and installing a  
 7 sampling port sealed in place with modeling clay. These sewer lateral sampling ports  
 8 remained in place throughout the field program. Indoor air samples were collected directly,  
 9 either by grab sampling with 1-L Summa canisters, or by using a HAPSITE Smart Plus  
 10 Gas Chromatograph/Mass Spectrometer (GC/MS) (Inficon, New York). In the latter case,  
 11 samples were collected into the instrument using the hand-held HAPSITE probe.

12  
 13 A total of 55 vapor/air samples were collected. Thirty-nine (39) of these were analyzed  
 14 on-site using the HAPSITE GC/MS (after Gorder and Dettenmaier, 2011). The remaining  
 15 16 samples collected in Tedlar bags and Summa canisters were shipped to the  
 16 TestAmerica laboratory in Sacramento, CA, a National Environmental Laboratory  
 17 Accreditation Program (NELAP) certified commercial analytical laboratory, for analysis by  
 18 USEPA Method TO-15 (USEPA, 1999). Tedlar bags were shipped for overnight delivery  
 19 and were transferred by the laboratory into Summa canisters to avoid exceeding holding  
 20 time limits. Due to operational difficulties with the HAPSITE GC/MS, no replicate samples  
 21 were analyzed both on site and by the offsite laboratory.

### 22 2.3 Liquid sampling and analysis.

23  
 24 Water and sewer liquid samples were collected from two existing monitoring wells (MW1A  
 25 and MW1C) and three sewer manholes, respectively. All samples were collected using  
 26 low-flow purge methods. Samples were shipped on ice to TestAmerica for analysis using  
 27 USEPA Method 8260B (USEPA, 1996).

### 28 2.4 Tracer study.

29  
 30 The tracer study was conducted using the Brookhaven National Laboratory's Air Infiltration  
 31 Measurement System which utilizes passive perfluorocarbon tracer (PFT) sources and  
 32 passive capillary adsorption tube samplers (CATS; Dietz et al., 1986, Winberry 1990). To  
 33 evaluate the interaction between the sewer and duplex, PFT sources, each emitting a  
 34 different perfluorocarbon compound, were deployed in 6 different areas (Table 1). To  
 35 deploy the sources in the manholes, the sources were attached to a weighted line and  
 36 suspended approximately 0.5 m above the top of the sewer line. Sources were deployed  
 37 on the first day of the study and remained in place throughout the testing period. After 4  
 38 hours, the CATS were deployed (Table 1, Figure S.1). The CATS were retrieved 93 hours  
 39 (approximately four days) after deployment and shipped to the Brookhaven National  
 40 Laboratory (certified through the New York State Department of Health Environmental  
 41 Laboratory Approval Program) for analysis by GC-Electron Capture Detector (ECD)  
 42 (Watson et al., 2007). Similar methodologies had previously been used to determine air  
 43 exchange rates for the structure (US EPA 2015a) but the previously used sources had  
 44 been removed long before the current testing.

45  
 46 **Table 1. Tracer Source and Sampler Locations**

Deployment Location	PFT Source Type	CATS ID
422 Main Floor	PDCB	10708, 00126
422 Basement	iPPCH	10251, 05395
422 SN Lateral	PTCH	00300, 05778

420 Main Floor	None	02783, 10249
420 Basement	ocPDCH	07471, 04441
420 SN Lateral	None	10379, 04295
SN Main Upstream	PMCH	01403, 07658
SN Main Downstream	PMCP	07694, 10689

1 Note: The PFT sources were deployed on the first day of the study and the CATS were deployed four hours  
2 later. The PFT sources and the CATS were retrieved 93 hours after CATS deployment. Locations are shown  
3 in Figure S.1. PFT source compound abbreviations are defined in the supporting materials.  
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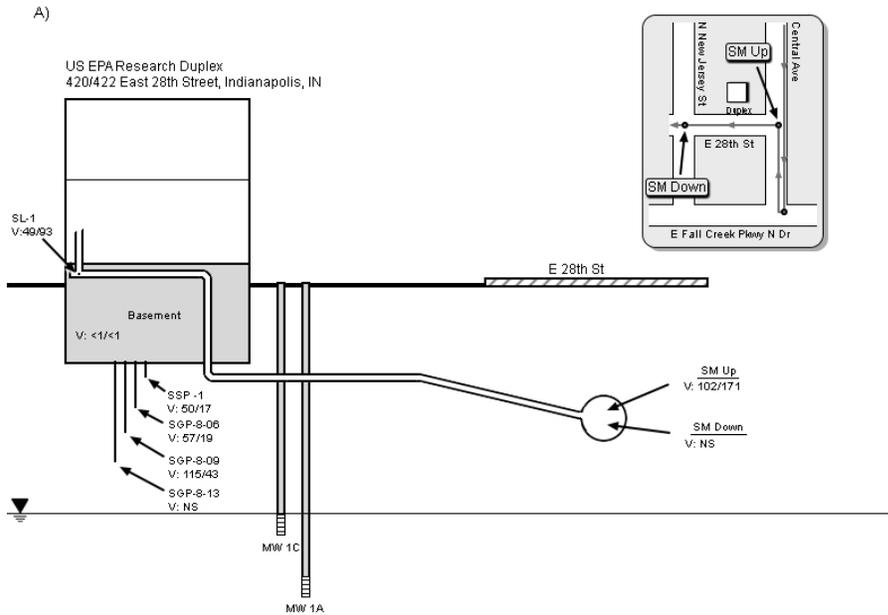
### 5 6 **3.0 Results**

7  
8 The field sampling program at the duplex consisted primarily of i) VOC concentration  
9 measurements of sewer manhole vapor, soil gas, indoor air, groundwater, and sewer  
10 liquid, and ii) a tracer study using PFT compounds released at the sewer manholes and  
11 inside the duplex. Sampling was conducted from June 12 to June 16, 2016. The field  
12 sampling program was complicated by two thunderstorm events that occurred on the  
13 afternoons of June 14 and June 15, which resulted in 2.4 inches and 3.0 inches of  
14 precipitation, respectively. Because the sewer line connected to the duplex is a combined  
15 storm and sanitary sewer, these rain events resulted in very high water flows through the  
16 sewer during both afternoons.  
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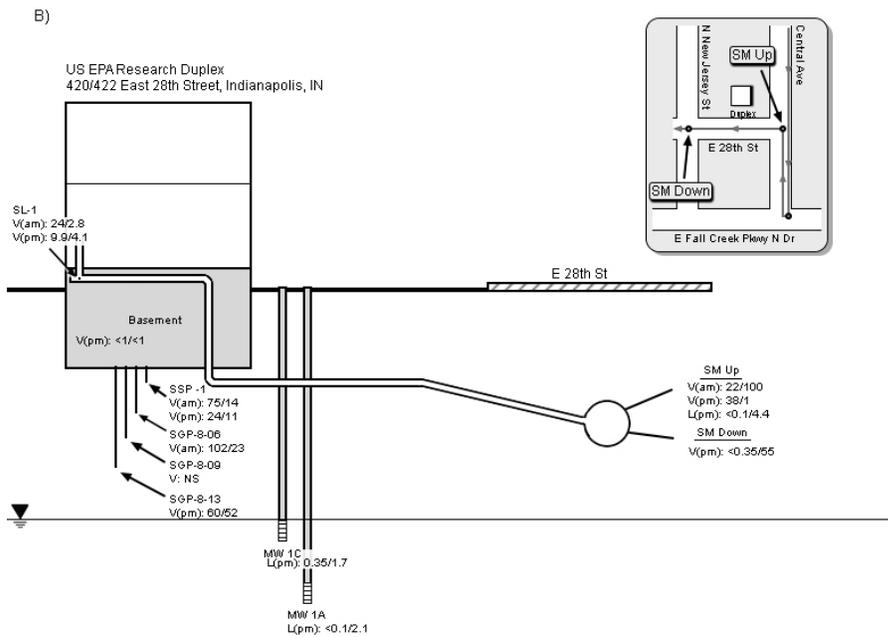
#### 18 *3.1 PCE and Chloroform in the Immediate Vicinity of the Duplex*

19 PCE and chloroform were previously identified as the primary constituents of concern for  
20 vapor intrusion at this site (USEPA 2012). PCE and chloroform concentration results for  
21 all samples are provided in Table S.1 and S.2. Figure 2 summarizes PCE and chloroform  
22 concentrations measured in vapor and liquid samples collected from the immediate vicinity  
23 of the duplex. PCE and chloroform concentrations measured in the sub-slab and soil gas  
24 sample points were similar to those measured at other times during 2016 as part of the  
25 long-term study of the duplex, however, these concentrations were lower than those  
26 measured at the same sample points in the earlier years of the study (see Figures S.2 and  
27 S.3). As shown in Figure 2, both PCE and chloroform concentrations in vapor samples  
28 collected from the sewer line were similar to those measured in soil gas samples collected  
29 from below the duplex. Before the two storm events, concentrations in the sewer were  
30 slightly higher than in soil gas and, after the storm events, concentrations in the soil gas  
31 were slightly higher than in the sewer. PCE and chloroform concentrations in the sewer  
32 lateral line in the duplex basement were lower than in the sewer manhole but higher than  
33 in indoor air. PCE and chloroform concentrations in groundwater and sewer liquids were  
34 measured only after the storm events. PCE concentrations were non-detect or less than  
35 1 ug/L in all sewer liquid samples. Chloroform concentrations were slightly higher in the  
36 sewer liquids (4.4 ug/L) than in the groundwater (1.7 and 2.1 ug/L).  
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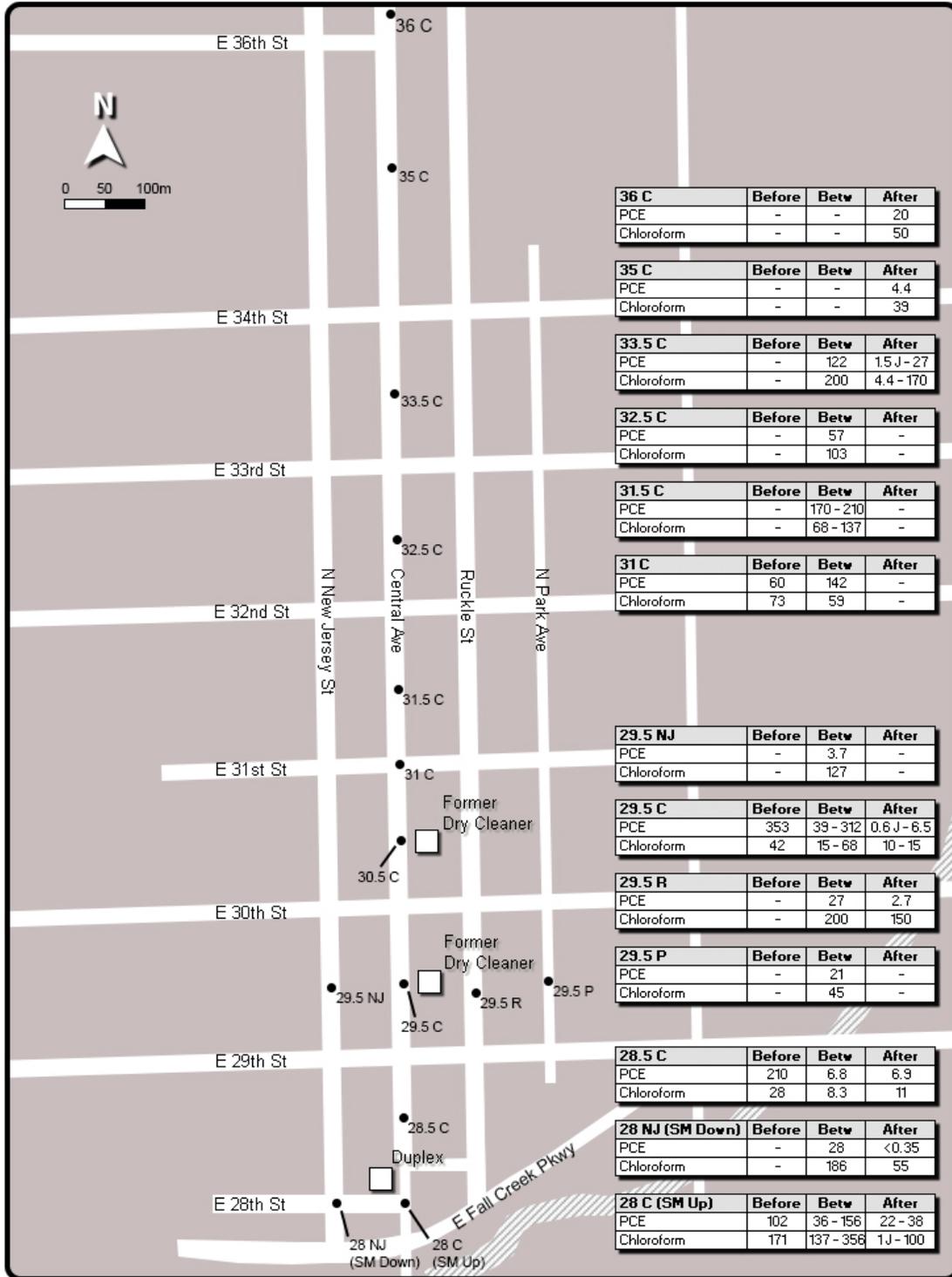
4  
5 Figure 2. VOC Concentration (PCE/Chloroform) results for samples collected in the  
6 immediate vicinity of the USEPA Research Duplex. V – vapor sample (ug/m<sup>3</sup>), L – Liquid  
7 sample (ug/L). Panel A: Samples collected 6/12-13/2016 before two storm events on 6/14  
8 and 6/15. Panel B: Samples collected on the morning (am) or afternoon (pm) of 6/16/2016  
9 after the two storm events. NS = Not sampled. SL-1 is a sample port installed in the  
10 sewer lateral line that runs through the 420 side of the duplex basement. “SM Up” and  
11 “SMDown” are the sewer manholes immediately upstream and downstream of the duplex.

Sewer vapor transport pathway

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*3.2 PCE in Sewer Manholes Away from the Duplex*

In addition to testing in and around the duplex, the field program included collection and analysis of vapor and liquid samples from sewer manholes further upstream of the duplex along Central Avenue and other adjacent streets (Figure 3). At least two former dry cleaner sites with documented PCE plumes in groundwater are located on Central Avenue north (upstream) of the duplex. PCE was detected in upstream manholes at concentrations ranging from 0.6 to 353 ug/m<sup>3</sup>. The highest PCE concentration (353 ug/m<sup>3</sup>) was measured in a manhole adjacent to one of the dry cleaner sites. In addition, PCE concentrations above 100 ug/m<sup>3</sup> were detected in several manholes upstream of the two known dry cleaner sites. At the duplex and adjacent to the two former dry cleaner sites, the manhole depths were shallower than the documented depth of groundwater in those areas, suggesting that PCE detected at these locations was not attributable to the local infiltration of groundwater into the sewer (Table S.3). However, information on groundwater depth was not available for manholes further upstream. As a result, it is not clear whether the PCE detected in manholes is primarily attributable to local infiltration of soil gas or upstream sources such as infiltration of contaminated groundwater or discharge of wastewater containing PCE. Similar to the manholes adjacent to the duplex, PCE concentrations in the upstream manholes were higher before the two storm events than after these events. Elevated chloroform concentrations were widely distributed across the manholes tested, consistent with discharges of chlorinated water and bleach into the sewer system as likely sources.



1  
2 Figure 3. VOC Concentration (PCE and Chloroform,  $\mu\text{g}/\text{m}^3$ ) results for vapor samples  
3 collected in the vicinity of the duplex. Before = Samples collected on June 13 or June 14  
4 prior to the first storm event. Betwn = samples collected on the morning of June 15 between  
5 the first and second storm events. After = samples collected on June 16 after the second  
6 storm event.  
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Sewer vapor transport pathway

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### 3.3 Results of Tracer Study

Six PFT compounds were used to evaluate air movement within the duplex and between the duplex and the sewer line. Source release locations and CATS locations are shown on Figure S.1. Both the sources and the CATS deployed in the two manholes were covered by storm water flow during the two storm events. Visual inspection of the CATS following the first storm event showed an absence of water inside the CATS tubes. However, when the CATS were collected on June 17, one CATS (ID 10689) from the downstream sanitary sewer manhole sample location had a thin film of water covering the opening of the tube that likely affected the tracer uptake for that tube. The results for this CATS are reported in the supplemental materials, but are not considered for the interpretation of the tracer study results.

At two CATS locations (SN Main Upstream and 422 SN Lateral), one of the two samplers was collected early, on June 15 at 11:30 am, in order to evaluate the effect of water inundation on the tracer release from the sources and the uptake by the CATS. The difference in average tracer concentrations for the samplers with different exposure durations was small (Relative Percent Differences of 10% to 52%) with no clear difference between sources in the sewer mains that were inundated by the storm events and sources in the house that were not. This suggests that the inundation events had only a minor effect on the rate of tracer release from the sources in the sewer mains. Additional information on the results from the tracer testing is provided in the Supplemental Materials.

The tracer study demonstrated air exchange between the sewer line and the duplex based on detection of tracer released in both upstream and downstream sewer manholes inside the duplex. Tracer attenuation factors were calculated for each of the two sewer manholes as the tracer concentration in the duplex divided by the tracer concentration in the sewer manhole. At each location, the tracer concentration was measured using the CATS deployed over the four-day test period (i.e., the tracer concentration was the average concentration over the four-day test period). Sewer to indoor air attenuation factors ranged from <0.001 to 0.006 for the upstream manhole and 0.010 to 0.021 for the downstream manhole (Table 2), indicating approximately 500x dilution of vapors from the upstream manhole to indoor air and 50x dilution of vapors from the downstream manhole. The sewer to indoor air attenuation factors were similar in the basement and main floor. The two storm events that occurred during the four-day tracer release period resulted in two periods of high storm water flows that completely filled the sewer line and backed water into the manholes. Although the tracer study documents gas exchange between the sewer line and the duplex, the attenuation factors measured may not be representative of more typical weather conditions when flows through the sewer are lower.

The tracer compounds released into the sewer manholes were detected at the sewer lateral sample points at concentrations higher than those detected inside the duplex demonstrating migration through the sewer lateral. Tracer concentrations detected in the sewer lateral sample points indicated similar magnitude of transport into the sewer lateral from the upstream manhole and the downstream manhole (see Supplemental Material, Tracer Study Report). It is not clear why higher amounts of tracer from the downstream manhole were detected inside the duplex. In addition, the tracer compound released directly into the sewer lateral inside the basement was not detected within the air of the duplex at any of the four sampling locations. This indicates limited leakage from the sewer lateral lines running through the basement of the duplex. Instead, the results suggest that

1 the sewer lateral leaks below the duplex foundation and that sewer vapors then enter the  
 2 duplex through the foundation.

3

4 **Table 2. Sewer Main to Indoor Air Attenuation Factors Measured Using**  
 5 **Perfluorocarbon Tracer Compounds**

Source Location	Duplex Location	Attenuation Factor
Sewer Manhole Upstream	422 Basement	0.004
	422 Main Floor	0.006
	420 Basement	<0.001
	420 Main Floor	<0.001
Sewer Manhole Downstream	422 Basement	0.015
	422 Main Floor	0.018
	420 Basement	0.010
	420 Main Floor	0.021

6

#### 7 **4.0 Discussion**

8

9 The tracer, sewer vapor, soil gas, and indoor air testing conducted during the field  
 10 investigation confirmed that the sewer line can serve as a local preferential pathway for  
 11 migration of volatile chemicals from the sewer main into the duplex. This is evident  
 12 because i) PCE and chloroform were detected at multiple locations within the sewer line  
 13 serving the duplex and ii) tracers released in the upstream and downstream manholes  
 14 were detected in the duplex sewer laterals and in indoor air. However, the migration  
 15 pathway is complex. Tracer released in the sewer lateral running through the basement  
 16 of the duplex was detected within the lateral, but not in any other location, suggesting  
 17 limited leakage from the lateral itself inside the duplex. Taken together, the tracer data  
 18 suggest that the sewer lateral line may leak at some point below the duplex foundation  
 19 followed by migration into the duplex by other mechanisms. The sewer manhole tracer  
 20 compounds were detected on the main floor of the duplex at concentrations that were 1.2x  
 21 to 1.8x higher than measured in the basement suggesting some transport of tracer  
 22 compounds to the main floor that by-passed the basement.

23

24 Tracer compounds released inside the duplex showed modest mixing between the  
 25 basement and the main floor. Tracer compounds released in the basement were detected  
 26 on the main floor at concentrations of 15 to 30% of those measured in the basement, while  
 27 the tracer compound release on the main floor was measured in the basement at only  
 28 2.5% of the main floor concentration (see Supplemental Material, Tracer Study Report).  
 29 During the multi-year study of the duplex, PCE concentrations on the main floor were  
 30 typically lower than in the basement, averaging about 50% of the basement concentration.  
 31 Chloroform concentrations on the main floor averaged about 80% of the concentration in  
 32 the basement, but were higher on the main floor than in the basement during  
 33 approximately 25% of the sample events. These data suggest that some PCE and  
 34 chloroform may reach the main floor through pathways that by-pass the basement (e.g.,  
 35 through wall gaps). However, the differences in distribution within the duplex between the  
 36 sewer manhole tracer compounds, PCE, and chloroform suggest that there may be some  
 37 differences in how these compounds enter the duplex and migrate within the duplex.

38

39 In addition to the June 2016 field program, prior testing at the duplex suggested a role for  
 40 the sewer line in transport of PCE and chloroform to the duplex. The prior test results

1 suggest that, at least during some time periods, the sewer line was the primary transport  
2 pathway from the VOC source to the building envelope:

- 3
- 4 • PCE and chloroform concentrations in sub-slab samples were commonly greater  
5 than or equal to those measured in matched deeper soil gas samples (Figure S.2,  
6 S.3, S.4, and S.5). This suggests an absence of upwards diffusion of VOCs from  
7 a local groundwater source and indicates, instead, an alternate mechanism for  
8 VOC vapor transport to the sub-slab soils. This pattern of VOC distribution below  
9 the residence was one line of evidence pointing to a preferential transport pathway  
10 at the ASU research house in Utah (Guo et al., 2015).
- 11 • When floor drains were tested in May 2011, PCE and chloroform concentrations  
12 in the first floor laundry area floor drain were each approximately 300 ug/m<sup>3</sup>. These  
13 concentrations were much higher than measured in indoor air and also higher than  
14 measured in sub-slab soil gas sample points during that immediate time frame.  
15 Although floor drains were plugged after this testing, this plugging would not affect  
16 transport of vapors through the sewer to a leak point below the foundation.

17  
18 In late 2012 and early 2013, testing of a newly-installed sub-slab depressurization system  
19 provided additional evidence for a preferential pathway for VOC transport to the duplex:

- 20
- 21 • Operation of the mitigation system consistently reduced indoor radon  
22 concentrations by more than 90%. However, episodic PCE vapor intrusion events  
23 occurred during operation of the mitigation system that were similar to those  
24 observed when the mitigation system was not operating (Figure S.6 and S.7).
- 25 • The mitigation system resulted in a large reduction in radon concentration in the  
26 soil gas below the duplex but had only a small effect on PCE and chloroform  
27 concentrations below the duplex (Figures S.8, S.9, and S.10). This suggests that  
28 the mitigation system was drawing PCE and chloroform vapors from a large  
29 reservoir such as the sewer line. The alternate interpretation that the mitigation  
30 system was primarily drawing air from greater depth is not consistent with the  
31 relatively uniform concentration of radon with depth premitigation (Figure S.8).
- 32 • The mass flux of PCE and chloroform captured by the mitigation system was 25 to  
33 50 times higher than the mass flux of these VOCs through the duplex in the  
34 absence of mitigation (USEPA, 2015b). This, again, suggests that the mitigation  
35 system was capturing PCE and chloroform from a large reservoir such as the  
36 sewer system.

37  
38 Combined, these observations indicate a clear role for the sewer line in transport of VOCs  
39 to the duplex. The 2016 field program results, however, were less definitive concerning  
40 the primary source of PCE and chloroform: a local groundwater plume vs. infiltration of  
41 contaminated groundwater into the sewer line at a location upstream of the duplex.  
42 Throughout the long-term study of the duplex, PCE concentrations in groundwater have  
43 generally been less than 1.5 ug/L while chloroform concentrations have ranged from <1  
44 ug/L to 3 ug/L. The detection of PCE in sewer liquids at a concentration well above 1 ug/L  
45 would have provided strong evidence that PCE was migrating through the sewer line. The  
46 sewer liquids collected during the field program from the upstream manhole contained  
47 non-detect PCE concentrations (<0.1 ug/L) and 4.4 ug/L of chloroform. However, these  
48 samples were collected only 24 hours after the second of the two storm events. PCE  
49 vapor concentrations were lower during this time period compared to before the storm  
50 events suggesting that the post-storm liquid concentrations may not be representative of  
51 sewer liquids during drier periods. PCE was detected in sewer vapor samples collected

1 from manholes along Central Avenue upstream of the duplex at concentrations up to 353  
2 ug/m<sup>3</sup> (Figure 3). Taken as a whole, the sewer test results suggest that PCE could be  
3 transported through the sewer line from upstream sources, but they do not demonstrate  
4 that this is occurring or that it is the primary source of PCE for vapor intrusion at the duplex.  
5 A longer monitoring period would be required to resolve this.

6  
7 While PCE in the sewer liquids would likely originate from infiltrating groundwater  
8 associated with an upstream plume, chloroform would likely be associated with domestic  
9 wastewater. Chloroform is a disinfection by-product commonly found in public water  
10 supplies at concentrations of 2 to 44 ug/L (ATSDR, 1997). In addition, chloroform is a  
11 reaction product of chlorine bleach cleaner and organic material (Odabasi, 2008). As a  
12 result, after a storm event, chloroform is likely to return to the sewer line more quickly than  
13 PCE. During the field program, chloroform concentrations in the sewer liquids (3.6 to 4.4  
14 ug/L) were approximately twice the concentration measured in groundwater at the duplex  
15 suggesting that the sewer is the more important source of chloroform for vapor intrusion.  
16 In fact, it is possible that the chloroform detected in groundwater is attributable to sewer  
17 exfiltration (Amick, 2000).

18  
19 Regardless of whether the sewer lines are transporting liquids from a remote source, the  
20 results of the field program and prior testing of the duplex confirm that the sewer line can  
21 act as a local reservoir and transport pathway for PCE and chloroform vapors from the  
22 subsurface source into the building envelope. In addition, elevated concentrations of PCE  
23 and chloroform were detected in sewer vapor samples at most of the manholes tested in  
24 the area. These results, as well as recent findings from other studies (Guo et al., 2015;  
25 Nielsen et al., 2014; Riis et al., 2010; McHugh et al., 2011; Pennell et al., 2013; McHugh  
26 et al., 2012), suggest that the role of sewer lines in vapor intrusion should be routinely  
27 evaluated as part of vapor intrusion investigations.

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37 of trade names or commercial products does not constitute endorsement or  
38 recommendation for use.

## 41 **Supplementary Materials**

42  
43 Supplementary materials to this article are available.

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**SUPPLEMENTAL MATERIALS**

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- Table S.1: Vapor Sample Results
  - Table S.2: Liquid Sample Results
  - Table S.3: Depth to Water in Manholes vs. Monitoring Wells
  - Figure S.1: Tracer Study Release and Sample Locations
  - Figure S.2: PCE concentrations over time at soil gas sample points SGP-8
  - Figure S.3: Chloroform concentrations over time at soil gas sample points SGP-8
  - Figure S.4: TO-17 PCE soil gas concentrations used in indoor air / soil gas attenuation factor calculations with multiple soil gas sample probes averaged at each depth. (Figure 8-10 from USEPA, 2015a)
  - Figure S.5: TO-17 Chloroform soil gas concentrations used in indoor air / soil gas attenuation factor calculations with multiple soil gas sample probes averaged at each depth. (Figure 8-13 from USEPA, 2015a)
  - Figure S.6: GC PCE in indoor air versus radon from stationary AlphaGUARDs (Figure 6-70 from USEPA 2015a)
  - Figure S.7: GC chloroform in indoor air versus radon from stationary AlphaGUARDs (Figure 6-69 from USEPA, 2015a)
  - Figure S.8: AlphaGUARD soil gas radon concentrations (pCi/L) used as denominator in attenuation factor calculations. (Figure 8-22 from USEPA, 2015a)
  - Figure S.9: TO-17 soil gas PCE concentrations. (Figure 8-25 from USEPA, 2015a)
  - Figure S.10: TO-17 soil gas chloroform concentrations. (Figure 8-28 from USEPA, 2015a)
- Tracer Study Report, ESTCP Vapor Intrusion Study – Indianapolis, Terry Sullivan, Brookhaven National Lab, 7 July 2016.