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

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Highlights

- **The sewer line is an important pathway for VOC transport at the USEPA duplex**
- **The importance of this pathway was not identified during prior study of the duplex**
- **Sewer lines should be routinely evaluated during vapor intrusion investigations**

Abstract

The role of sewer lines as preferential pathways for vapor intrusion is poorly understood. Although the importance of sewer lines for volatile organic compound (VOC) transport has been documented at a small number of sites with vapor intrusion, sewer lines are not routinely sampled during most vapor intrusion investigations. We have used a tracer study and VOC concentration measurements to evaluate the role of the combined sanitary / storm sewer line in VOC transport at the USEPA vapor intrusion research duplex in Indianapolis, Indiana. The results from the tracer study demonstrated gas migration from the sewer main line into the duplex. The migration pathway appears to be complex and may include leakage from the sewer lateral at a location below the building foundation. Vapor samples collected from the sewer line demonstrated the presence of tetrachloroethene (PCE) and chloroform in the sewer main in front of the duplex and at multiple sample locations within the sewer line upstream of the duplex. These test results combined with results from the prior multi-year study of the duplex indicate that the sewer line plays an important role in transport of VOCs from the subsurface source to the immediate vicinity of the duplex building envelope.

**Key Words: preferential pathway, Indianapolis, utility tunnel**

1.0 Introduction

Sewer vapor transport pathway

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 though 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).
47

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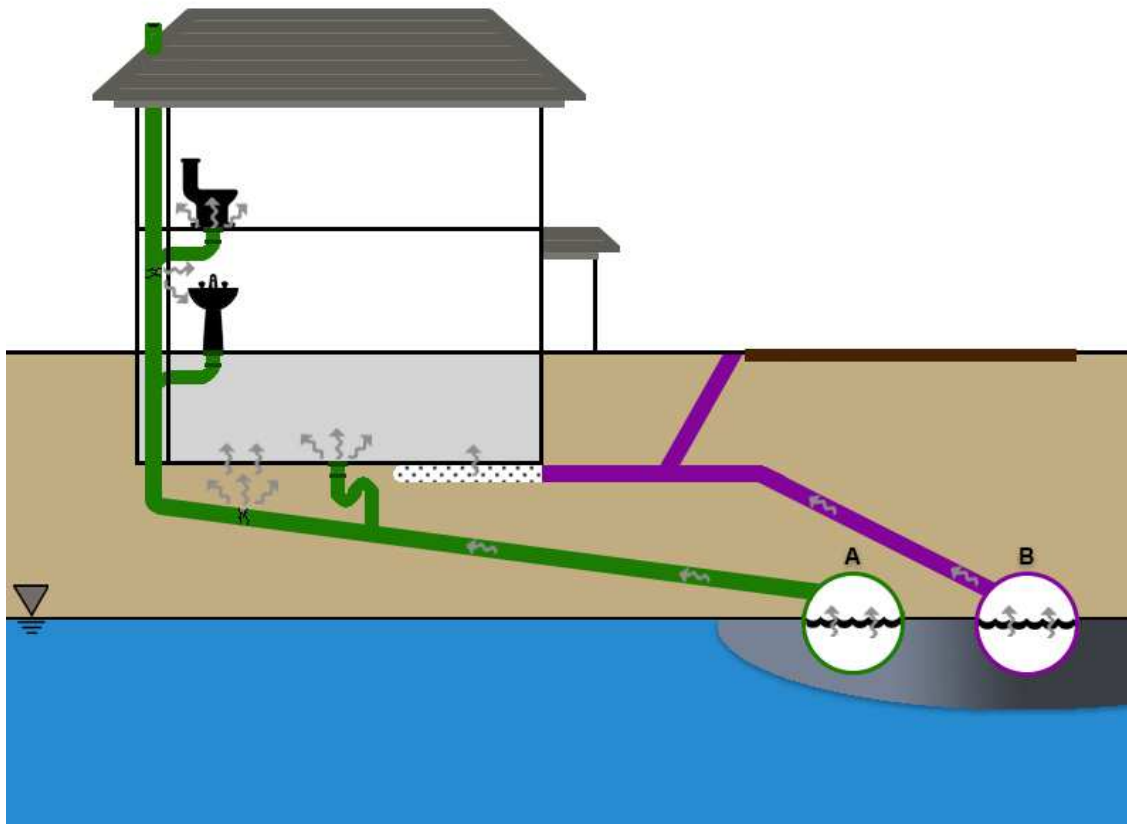
Figure 1. Conceptual illustration of sewer preferential pathways for vapor intrusion. A) Most residences (i.e., those without septic tanks), are connected to the sanitary (or combined storm and sanitary) sewer system. B) Some residences have foundation drain systems connected to land drain or storm sewer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

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

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

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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^3 for PCE, much higher than the 1.2 ug/m^3 upper-bound
20 concentration predicted using the USEPA 95th 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^3) 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

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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

23 *2.3 Liquid sampling and analysis.*
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

29 *2.4 Tracer study.*
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

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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.
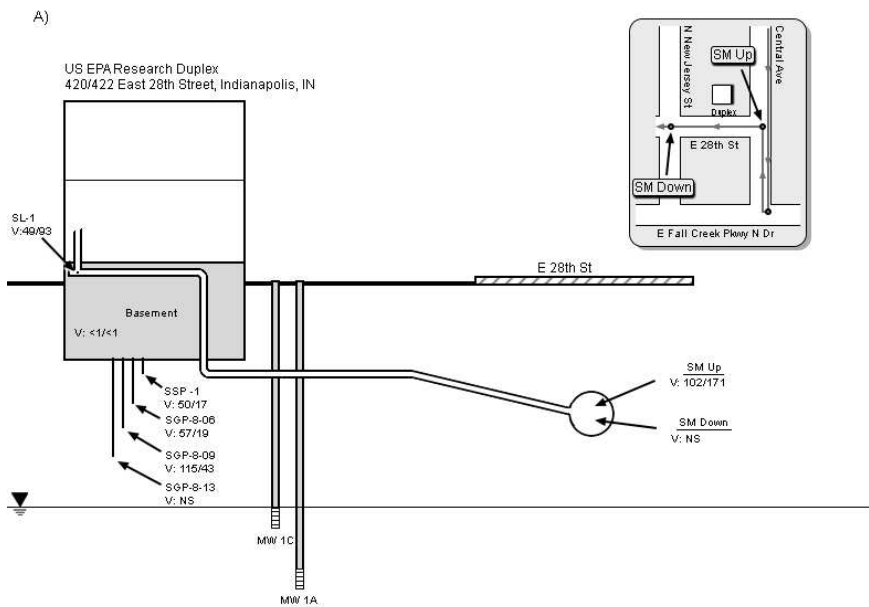4
5
6   **3.0 Results**
7
8   The field sampling program at the duplex consisted primarily of i) VOC concentration
9   measurements of sewer manhole vapor, soil gas, indoor air, groundwater, and sewer
10   liquid, and ii) a tracer study using PFT compounds released at the sewer manholes and
11   inside 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
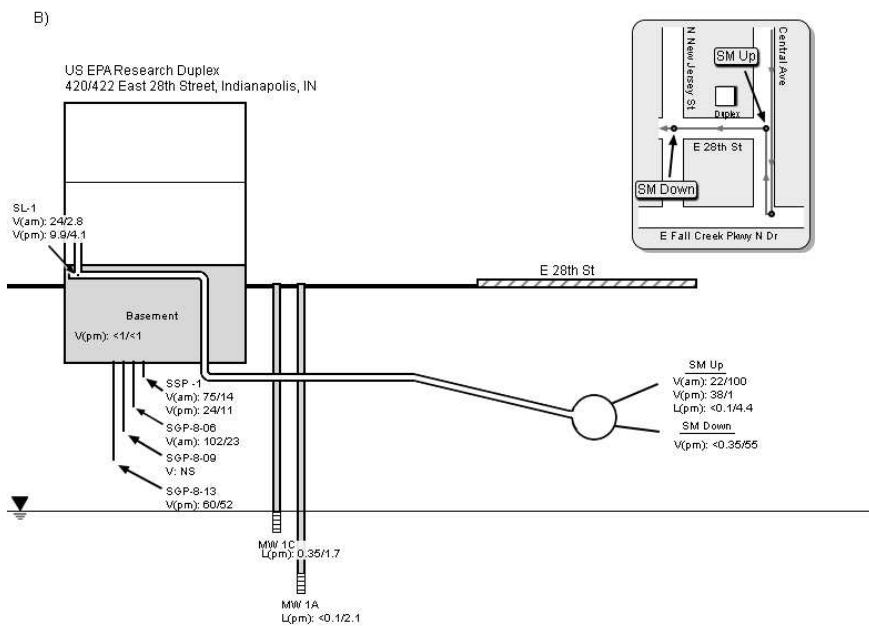16   sewer during both afternoons.
17
18   *3.1 PCE and Chloroform in the Immediate Vicinity of the Duplex*
19   PCE and chloroform were previously identified as the primary constituents of concern for
20   vapor intrusion at this site (USEPA 2012). PCE and chloroform concentration results for
21   all 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).
37

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1

A)

US EPA Research Duplex
420/422 East 28th Street, Indianapolis, IN

SL-1
V:49/93

Basement
V: <1/<1

SSP -1
V: 50/17
SGP-8-06
V: 57/19
SGP-8-09
V: 115/43
SGP-8-13
V: NS

MW 1C

MW 1A

E 28th St

SM Up
V: 102/171

SM Down
V: NS

N New Jersey St · Central Ave · SM Up · Duplex · E 28th St · SM Down · E Fall Creek Pkwy N Dr

2
3

B)

US EPA Research Duplex
420/422 East 28th Street, Indianapolis, IN

SL-1
V(am): 24/2.8
V(pm): 9.9/4.1

Basement
V(pm): <1/<1

SSP -1
V(am): 75/14
V(pm): 24/11
SGP-8-06
V(am): 102/23
SGP-8-09
V: NS
SGP-8-13
V(pm): 60/52

MW 1C
L(pm): 0.35/1.7

MW 1A
L(pm): <0.1/2.1

E 28th St

SM Up
V(am): 22/100
V(pm): 38/1
L(pm): <0.1/4.4
SM Down
V(pm): <0.35/55

N New Jersey St · Central Ave · SM Up · Duplex · E 28th St · SM Down · E Fall Creek Pkwy N Dr
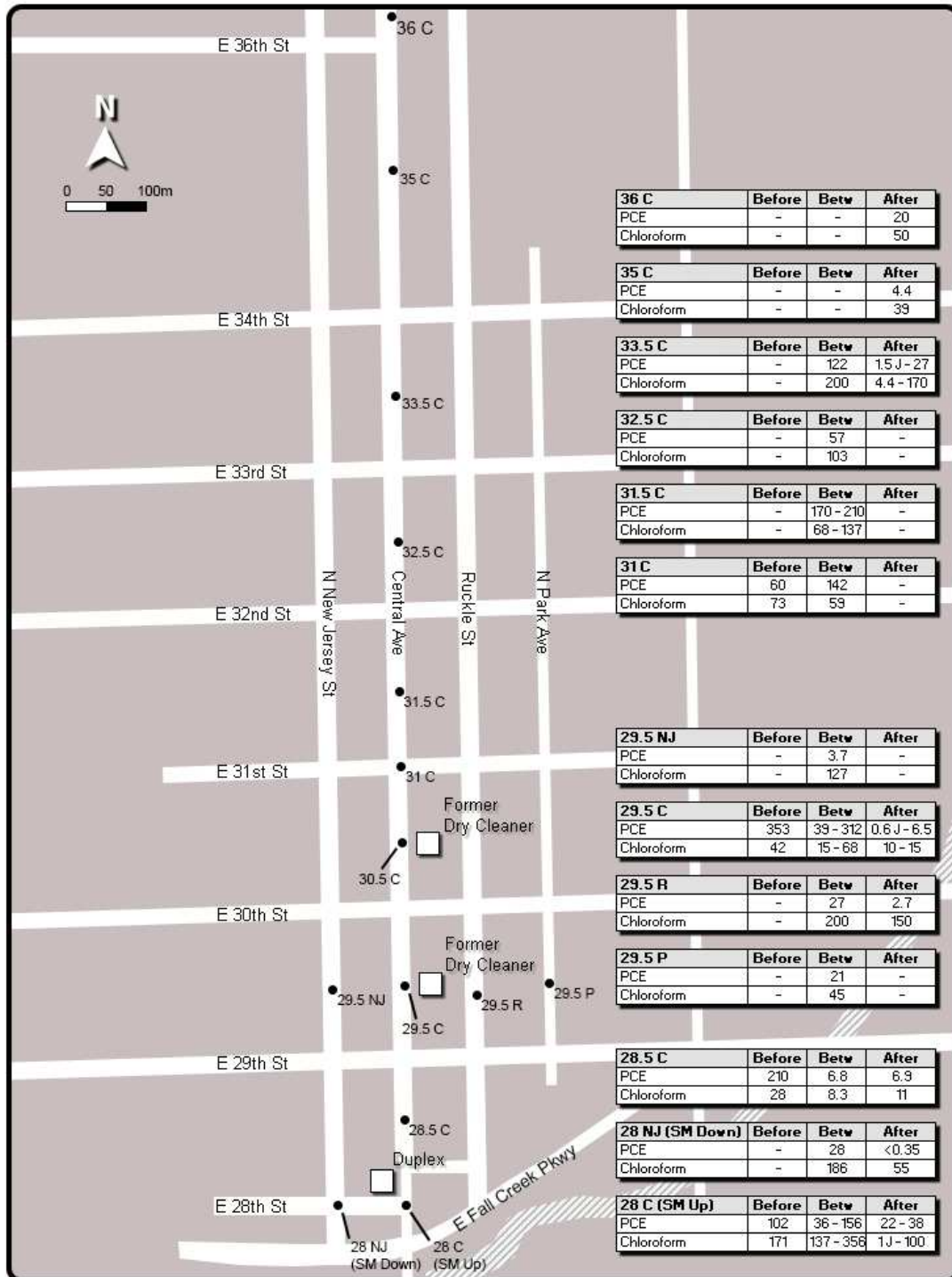
4
5 Figure 2. VOC Concentration (PCE/Chloroform) results for samples collected in the
6 immediate vicinity of the USEPA Research Duplex. V – vapor sample (ug/m^3), L – Liquid
7 sample (ug/L). Panel A: Samples collected 6/12-13/2016 before two storm events on 6/14
8 and 6/15. Panel B: Samples collected 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.

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1
2
3   *3.2 PCE in Sewer Manholes Away from the Duplex*
4   In addition to testing in and around the duplex, the field program included collection and
5   analysis of vapor and liquid samples from sewer manholes further upstream of the duplex
6   along Central Avenue and other adjacent streets (Figure 3). At least two former dry
7   cleaner sites with documented PCE plumes in groundwater are located on Central Avenue
8   north (upstream) of the duplex.   PCE was detected in upstream manholes at
9   concentrations ranging from 0.6 to 353 ug/m^3. The highest PCE concentration (353 ug/m^3)
10 was measured in a manhole adjacent to one of the dry cleaner sites. In addition, PCE
11 concentrations above 100 ug/m^3 were detected in several manholes upstream of the two
12 known dry cleaner sites. At the duplex and adjacent to the two former dry cleaner sites,
13 the manhole depths were shallower than the documented depth of groundwater in those
14 areas, suggesting that PCE detected at these locations was not attributable to the local
15 infiltration of groundwater into the sewer (Table S.3).   However, information on
16 groundwater depth was not available for manholes further upstream. As a result, it is not
17 clear whether the PCE detected in manholes is primarily attributable to local infiltration of
18 soil gas or upstream sources such as infiltration of contaminated groundwater or discharge
19 of wastewater containing PCE. Similar to the manholes adjacent to the duplex, PCE
20 concentrations in the upstream manholes were higher before the two storm events than
21 after these events. Elevated chloroform concentrations were widely distributed across the
22 manholes tested, consistent with discharges of chlorinated water and bleach into the
23 sewer system as likely sources.
24
25

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36 C	Before	Betw	After
PCE	–	–	20
Chloroform	–	–	50

35 C	Before	Betw	After
PCE	–	–	4.4
Chloroform	–	–	39

33.5 C	Before	Betw	After
PCE	–	122	1.5 J - 27
Chloroform	–	200	4.4 - 170

32.5 C	Before	Betw	After
PCE	–	57	–
Chloroform	–	103	–

31.5 C	Before	Betw	After
PCE	–	170 - 210	–
Chloroform	–	68 - 137	–

31 C	Before	Betw	After
PCE	60	142	–
Chloroform	73	59	–

29.5 NJ	Before	Betw	After
PCE	–	3.7	–
Chloroform	–	127	–

29.5 C	Before	Betw	After
PCE	353	39 - 312	0.6 J - 6.5
Chloroform	42	15 - 68	10 - 15

29.5 R	Before	Betw	After
PCE	–	27	2.7
Chloroform	–	200	150

29.5 P	Before	Betw	After
PCE	–	21	–
Chloroform	–	45	–

28.5 C	Before	Betw	After
PCE	210	6.8	6.9
Chloroform	28	8.3	11

28 NJ (SM Down)	Before	Betw	After
PCE	–	28	<0.35
Chloroform	–	186	55

28 C (SM Up)	Before	Betw	After
PCE	102	36 - 156	22 - 38
Chloroform	171	137 - 356	1 J - 100

1
2 Figure 3. VOC Concentration (PCE and Chloroform, ug/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. Btwn = 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.
7

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1
2 *3.3 Results of Tracer Study*
3 Six PFT compounds were used to evaluate air movement within the duplex and between
4 the duplex and the sewer line. Source release locations and CATS locations are shown
5 on Figure S.1. Both the sources and the CATS deployed in the two manholes were
6 covered by storm water flow during the two storm events. Visual inspection of the CATS
7 following the first storm event showed an absence of water inside the CATS tubes.
8 However, when the CATS were collected on June 17, one CATS (ID 10689) from the
9 downstream sanitary sewer manhole sample location had a thin film of water covering the
10 opening of the tube that likely affected the tracer uptake for that tube. The results for this
11 CATS are reported in the supplemental materials, but are not considered for the
12 interpretation of the tracer study results.
13
14 At two CATS locations (SN Main Upstream and 422 SN Lateral), one of the two samplers
15 was collected early, on June 15 at 11:30 am, in order to evaluate the effect of water
16 inundation on the tracer release from the sources and the uptake by the CATS. The
17 difference in average tracer concentrations for the samplers with different exposure
18 durations was small (Relative Percent Differences of 10% to 52%) with no clear difference
19 between sources in the sewer mains that were inundated by the storm events and sources
20 in the house that were not. This suggests that the inundation events had only a minor
21 effect on the rate of tracer release from the sources in the sewer mains. Additional
22 information on the results from the tracer testing is provided in the Supplemental Materials.
23
24 The tracer study demonstrated air exchange between the sewer line and the duplex based
25 on detection of tracer released in both upstream and downstream sewer manholes inside
26 the duplex. Tracer attenuation factors were calculated for each of the two sewer manholes
27 as the tracer concentration in the duplex divided by the tracer concentration in the sewer
28 manhole. At each location, the tracer concentration was measured using the CATS
29 deployed over the four-day test period (i.e., the tracer concentration was the average
30 concentration over the four-day test period). Sewer to indoor air attenuation factors
31 ranged from <0.001 to 0.006 for the upstream manhole and 0.010 to 0.021 for the
32 downstream manhole (Table 2), indicating approximately 500x dilution of vapors from the
33 upstream manhole to indoor air and 50x dilution of vapors from the downstream manhole.
34 The sewer to indoor air attenuation factors were similar in the basement and main floor.
35 The two storm events that occurred during the four-day tracer release period resulted in
36 two periods of high storm water flows that completely filled the sewer line and backed
37 water into the manholes. Although the tracer study documents gas exchange between
38 the sewer line and the duplex, the attenuation factors measured may not be representative
39 of more typical weather conditions when flows through the sewer are lower.
40
41 The tracer compounds released into the sewer manholes were detected at the sewer
42 lateral sample points at concentrations higher than those detected inside the duplex
43 demonstrating migration through the sewer lateral. Tracer concentrations detected in the
44 sewer lateral sample points indicated similar magnitude of transport into the sewer lateral
45 from the upstream manhole and the downstream manhole (see Supplemental Material,
46 Tracer Study Report). It is not clear why higher amounts of tracer from the downstream
47 manhole were detected inside the duplex. In addition, the tracer compound released
48 directly into the sewer lateral inside the basement was not detected within the air of the
49 duplex at any of the four sampling locations. This indicates limited leakage from the sewer
50 lateral lines running through the basement of the duplex. Instead, the results suggest that

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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 though 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

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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^3. 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

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1   from manholes along Central Avenue upstream of the duplex at concentrations up to 353
2   ug/m^3 (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.
28
29
30   **Acknowledgements**
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41   **Supplementary Materials**
42
43   Supplementary materials to this article are available.
44
45   **References**
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1   **SUPPLEMENTAL MATERIALS**
2
3   Table S.1: Vapor Sample Results
4   Table S.2: Liquid Sample Results
5   Table S.3: Depth to Water in Manholes vs. Monitoring Wells
6
7   Figure S.1: Tracer Study Release and Sample Locations
8   Figure S.2: PCE concentrations over time at soil gas sample points SGP-8
9   Figure S.3: Chloroform concentrations over time at soil gas sample points SGP-8
10   Figure S.4: TO-17 PCE soil gas concentrations used in indoor air / soil gas attenuation
11   factor calculations with multiple soil gas sample probes averaged at each depth. (Figure
12   8-10 from USEPA, 2015a)
13   Figure S.5: TO-17 Chloroform soil gas concentrations used in indoor air / soil gas
14   attenuation factor calculations with multiple soil gas sample probes averaged at each
15   depth. (Figure 8-13 from USEPA, 2015a)
16   Figure S.6: GC PCE in indoor air versus radon from stationary AlphaGUARDs (Figure
17   6-70 from USEPA 2015a)
18   Figure S.7: GC chloroform in indoor air versus radon from stationary AlphaGUARDs
19   (Figure 6-69 from USEPA, 2015a)
20   Figure S.8: AlphaGUARD soil gas radon concentrations (pCi/L) used as denominator in
21   attenuation factor calculations. (Figure 8-22 from USEPA, 2015a)
22   Figure S.9: TO-17 soil gas PCE concentrations. (Figure 8-25 from USEPA, 2015a)
23   Figure S.10: TO-17 soil gas chloroform concentrations. (Figure 8-28 from USEPA,
24   2015a)
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Sewer vapor transport pathway

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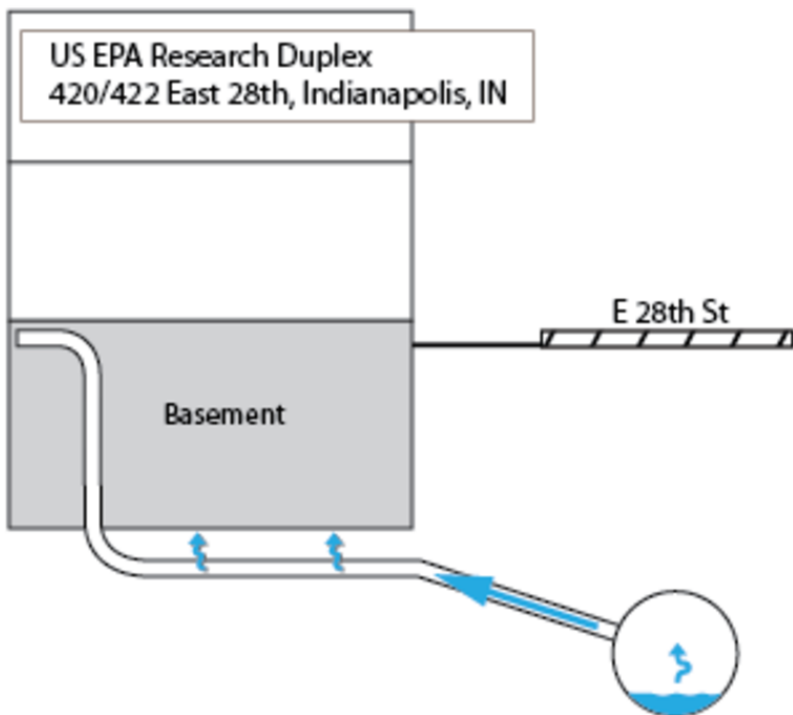
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