Vapor Intrusion in Homes over Gasoline-Contaminated Ground Water in Stafford, New Jersey

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Abstract

The potential for chemical vapor intrusion from contaminated ground water to the interior of homes was investigated at a site with a leaking underground gasoline storage tank in Stafford Township, New Jersey. This location exhibited conditions favorable to vapor intrusion, with sand soil and a water table depth of 3.3 m. Concentrations of volatile organic chemicals in the ground water were as high as 82 mg/L for total benzene, toluene, ethylbenzene, and xylene (BTEX) and up to 590 mg/L for methyl-*t*-butyl ether (MTBE). Soil vapor samples at multiple depths were taken adjacent to several homes. Inside the homes, air samples were taken on the main floor, in the basement, and under the foundation slab. Despite high ground water concentrations, only one home had measurable impacts to indoor air quality attributable to some of the ground water contaminants. In this house, the BTEX chemicals were not detected in the basement, indicating a lack of indoor air impacts from the ground water for these chemicals. Oxygen measurements suggested that degradation attenuated these chemicals as they diffused through the vadose zone. However, MTBE, 2,2,4-trimethylpentane (isooctane), and cyclohexane were found in the indoor air. The first two of these chemicals served as gasoline-specific tracers and indicated that vapor intrusion was occurring. Attenuation factors (the ratio of the indoor air concentration to a source soil vapor concentration) for the BTEX chemicals between the ground water and the indoor air were $<1 \times 10^{-5}$, and for MTBE was 1.2×10^{-5}. Attenuation factors between the deep-soil vapor and the basement air were as follows: BTEX compounds, $<1 \times 10^{-5}$; MTBE, 2.2×10^{-5}; 2,2,4-trimethylpentane, 3.6×10^{-4}; and cyclohexane, 1.2×10^{-4}. Attenuation factors between the subslab vapor and the basement air were 7 to 8×10^{-3}.

Introduction

The U.S. EPA has recently released draft guidance for evaluating contaminant vapor intrusion into indoor air, which includes ground water screening levels for various volatile organic chemicals (VOCs) when the ground water flows under occupied structures (U.S. EPA 2002). Concentrations of contaminants in ground water above the screening levels indicate the need for further investigation in order to determine whether there is a concern with indoor air quality. However, the U.S. EPA warns against using the document for estimating the impacts of petroleum-contaminated ground water (and soil) to indoor air because the procedures used for estimating screening numbers do not include the effects of biodegradation of these chemicals. Biodegradation has been shown to be a predominant fate mechanism for aromatic petroleum hydrocarbon vapors as they diffuse through the soil column (Ririe et al. 2002; Fitzpatrick and Fitzgerald 2002; Roggemans et al.

2001; Hers et al. 2000; Lahvis et al. 1999; DeVaull et al. 1997; Ostendorf and Kampbell 1991). By not including this mechanism, the U.S. EPA procedures yield screening levels that may be lower than necessary.

In order to contribute to the information database pertaining to indoor impacts from petroleum-contaminated ground water, the vapor intrusion pathway was studied at a site with a leaking underground storage tank in Stafford Township, New Jersey. Attenuation factors (the ratio of the indoor air concentration to a source soil vapor concentration) were determined for benzene, toluene, ethylbenzene, and xylene (BTEX) and the gasoline-related chemicals methyl-*t*-butyl ether (MTBE), 2,2,4-trimethylpentane, and cyclohexane. Additionally, the study included the measurement of ancillary ground water and soil vapor parameters and the collection of meterological and building depressurization data.
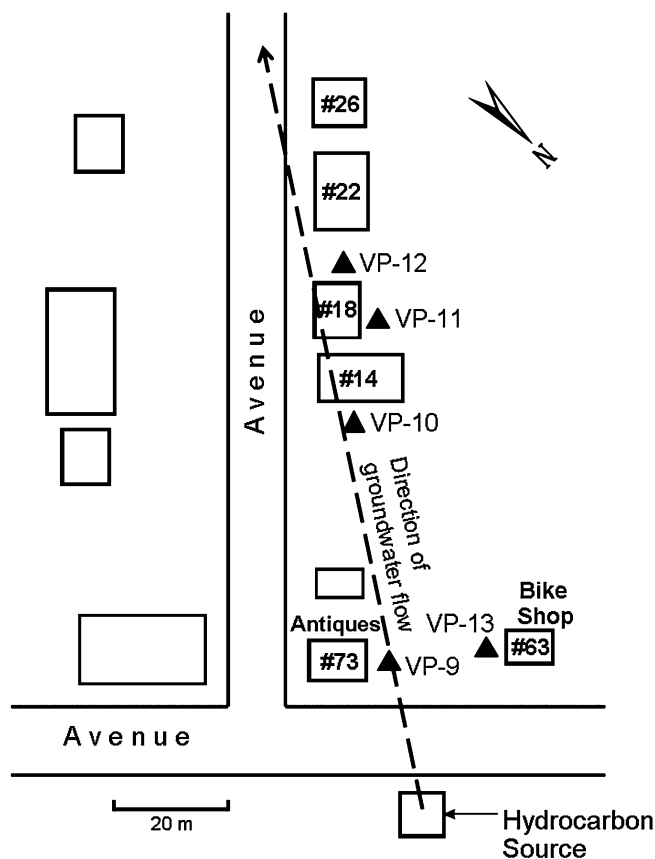
Description of Site

The area under study was near a gasoline station in Stafford Township, New Jersey, where removal of a

4000-gallon gasoline tank confirmed the presence of soil and ground water contamination (Figure 1). The neighborhood downgradient from the source consisted of a mixture of small commercial and residential structures, with a mixture of foundations including basements (extending to a depth of 1.7 m below the ground surface), slab-on-grade construction, and crawlspaces. Soil borings indicated the presence of unconsolidated sand through the entire vadose zone. The U.S. Department of Agriculture (USDA) describes the surficial soil at this location as Downer loamy sand (USDA 1999). The site was located above the Kirkwood-Cohansey Aquifer, a large unconfined sand aquifer that has an outcrop area over nearly the entire outer Coastal Plain of southern New Jersey (New Jersey Geological Survey 2004a, 2004b). The water table was shallow (~3.3 m), and the estimated Darcy ground water flow was 100 to 150 m/year in an SSW direction, based on spatial data layers of estimated hydraulic conductivities and hydraulic gradients for this aquifer (Vyas et al. 2004; Spayd and Johnson 2003). Given the permeable soil, the proximity of several buildings to the contaminant source (as close as 25 m), and the short transport distance from the water table to building foundations (1.6 m for buildings with basements), the vapor intrusion pathway was expected to be an exposure pathway of concern.

Methods

A coordinated program of ground water, soil, soil vapor, and indoor and outdoor ambient air sampling was undertaken in October 2002 for three homes (buildings #14, #18, and #22, Figure 1) and two small commercial buildings (structures #63 and #73) located above the contaminated ground water plume. (Building #73 was a house used as an antique shop.) Ground water, soil and soil vapor samples were taken on the same day, 1 to 3 m laterally from each of the five buildings studied. Indoor air and sub-slab vapor samples were taken within a few days of the exterior sampling. Continuous meteorological data, including atmospheric pressure, temperature, wind velocity, wind direction, and precipitation, were taken from the National Weather Service Atlantic City airport weather station, 39 km away. This location was determined to be meteorologically similar to the study location via inspection of weather maps of this region during the study event. Additionally, both locations have similar estimated average wind speeds (U.S. Department of Energy 2003).

Collection of shallow ground water and soil samples for analysis of volatiles, and the installation of soil vapor probe implants, was accomplished using the Geoprobe® system. Soil cores were taken from all five locations and screened for hydrocarbons at periodic depth intervals using a photoionization detector (PID) and a dry headspace vapor test. Soil samples were taken at 3-m depth from the VP-9 and VP-13 soil cores for volatiles analysis using ENCORE® samplers and U.S. EPA Method 8260B (U.S. EPA 1997). Additional soil was collected for moisture retention tests and organic carbon analysis.

Ground water (the top 1 m) was sampled by drawing water through either stainless steel or slotted polyvinyl chloride (PVC) Geoprobe® screens. During purging of the sample point, the pH and dissolved oxygen levels were measured. Subsequently, ground water samples were collected manually using a Waterra check valve and tubing and analyzed using U.S. EPA Method 8260B.

For soil vapor sampling, implants constructed of 15-cm-long by 1.3-cm-diameter cylindrical stainless steel screens were used (Geoprobe Model AT86) and connected to Summa canisters at the ground surface using polyethylene tubing. They were installed at 1, 2, and 3-m depth at locations VP-9 and VP-10, and at 3-m depth at the other locations. The implants were surrounded by sand, and the remainder of the borehole was filled with bentonite. Before sampling, the implant and tubing were purged with 1.5 volumes of soil gas. One-hour soil vapor samples were taken using 6-L Summa canisters. Samples were analyzed using U.S. EPA Method TO-15 (U.S. EPA 1999). Oxygen measurements were taken of the soil vapor by filling a 1-L Tedlar bag and then connecting it to a VRAE-Model L-R070406 combustible gas monitor.

Before taking indoor air samples, a survey of each building was taken in order to identify potential indoor sources of volatile organic compounds. No indoor gasoline storage was observed. Summa canisters (6 L) were used to take 24-h indoor, subslab, and outdoor ambient air samples. These were analyzed using U.S. EPA Method TO-15. For structures with concrete floor basements (#73, #14, and #18), both basement and ground floor samples were taken. Structures #73 and #18 also had partial crawlspaces open to the basement (~1.2 m above basement floor), with

Figure 1. Buildings studied and borehole locations in Stafford Township, New Jersey.

exposed soil. Building #22 had an unlined (earthen) crawl-space under the entire structure, and a sample was taken at that location and on the main floor. Building #63 had slab-on-grade construction; only a ground floor sample was taken. For all buildings except #22, subslab vapor samples were taken simultaneously with the indoor air samples. A 1-cm hole was drilled through the foundation floor of the building in a central location. Slab thicknesses were ~10 cm. The end of a length of Teflon®-lined tubing (~1-cm outer diameter) was wrapped with Teflon tape and tightly inserted into the drilled hole. The tubing was then connected to the Summa canisters. The low sampling flow rate (4.2 mL/min) and the dry sand observed under the slab resulted in minimal resistance to subslab vapor sampling.

For selected structures (#73, #22, and #14), differential pressure measurements between the outdoor and the indoor air were taken during sampling, using an Omniguard III differential pressure recorder. For buildings #73 and #14, the pressure difference between the basement and the outdoor air was measured. For building #14, the subslab to basement pressure differential was also measured. For building #22, the pressure differential between the crawl-space and the indoor air was measured. To connect to the exterior, 0.6-cm polyethylene tubing was run through a small crack in an almost closed window. The exterior end of the tubing was shielded from wind by placing it in the interior of a large PVC pipe (30 cm long by 10-cm diameter).

Outdoor ambient air samples (24 h) were taken using 6-L Summa canisters adjacent to buildings #73 and #22. These samples were analyzed using U.S. EPA Method TO-15.

Results and Discussion

The Stafford Township site, although small, was selected for study because it exhibited several features that would promote indoor air impacts from contaminated ground water. These features included sand soil through the entire soil column, a shallow water table, basements in several of the buildings that reduced the transport distance between the water table and the building foundation to ~1.6 m, and high concentrations of gasoline constituents in ground water. Five homes were subjected to both indoor air sampling and exterior sampling of soil vapor and ground water in order to elucidate concentration patterns and attenuation factors for the vapor intrusion pathway.

The study was conducted after 2 months of near-normal rainfall that was preceded by 2 months where rainfall was 40% of normal. No rainfall occurred at least 2 d prior to sampling events. Thus, water table elevations may have been slightly lower than normal, while soil moisture levels were expected to be nearly normal for the time of year sampled. All buildings were occupied during the sampling, so doors were periodically opened. Nighttime temperatures were between −1°C and +4°C, and daytime temperatures were typically 7°C to 16°C. These temperatures were ~3°C cooler than normal. Due to the cool weather, windows were largely, but not entirely, closed, and heating

systems (natural gas–fueled forced air or oil-fueled hot water radiant) were under moderate use. The average daily wind speed during indoor air sampling at the Atlantic City weather station ranged from 2 to 6 m/s, and barometric pressure variations were moderate (1010 to 1030 mbar). Except for somewhat breezy and slightly cooler than normal weather, the environmental conditions important for vapor intrusion sampling were judged to be near normal for that time of the year.

Results from the PID screening of the soil cores showed high levels of hydrocarbon vapors at 2.7- to 3.3-m depth at location VP-9 (Table 1). The remaining depths at location VP-9 and most depths at VP-13 and VP-10 showed somewhat elevated vapor levels but were not indicative of residual non–aqueous phase liquid (NAPL). Vapor concentrations at VP-11 and VP-12 were low. Based on these results, soil samples were taken just above the water table at VP-9 and VP-13. Results from these analyses confirmed the presence of contamination at location VP-9 just above the water table (Table 2). This was assumed to be residual NAPL resulting from water table fluctuations. Otherwise, the soil analyses and the PID readings determined that the source of the contamination was below the water table. The soil organic carbon content was low (0.04% to 0.68%), and the soil moisture-holding capacity was low (total porosity of 0.35 to 0.4 [v/v], field capacity moisture of 0.04 to 0.05 [v/v], residual water saturation of 0.005 to 0.017 [v/v]).

Shallow ground water sampling indicated BTEX concentrations in the milligram per liter range under buildings #63, #73, and #14 (Figure 1; Table 2), which dropped off rapidly under the remaining two buildings studied (#18 and #22). MTBE concentrations remained above 1 mg/L until passing under building #18.

Measurement of supplementary ground water parameters indicated slightly acidic conditions (pH 6.0 to 6.5) and

Table 1
PID Screening of Soil Samples Taken from Soil Cores at Stafford Township, New Jersey, October, 2002[1]

| Depth (m) | Location | | | | |
	VP-9	VP-13	VP-10	VP-11	VP-12
0–0.3	1.6	1.3	9	0.4	0.4
0.3–0.6	1.2	0.6	9.1	0.4	0.4
0.6–0.9	2.5	1.6	9.2	0.4	0.2
0.9–1.2	32	89.2	2.2	0.4	0.5
1.2–1.5	56	8.3	3.9	0.4	0.5
1.5–1.8	75	28	16.7	0.5	0.6
1.8–2.1	33.1	88.6	10.5	0.4	0.4
2.1–2.4	289	3.8	11.8	0.4	0.6
2.4–2.7	420	94.6	7.9	0.8	0.3
2.7–3.0	3928	116	6.9	0.5	0.5
3.0–3.3	1017	248	3.3	1.3	0.8

[1]Results are hydrocarbon concentrations in ppm; PID calibrated against 100% isobutylene with 10.2-eV lamp.

Table 2
Concentrations of Selected Petroleum-Related VOCs in Air, Water, and Soil at Five Properties Impacted by Gasoline-Contaminated Ground Water in Stafford Township, New Jersey, October, 2002[1]

Location	Analyte	Soil (3-m depth) (µg/kg)	Shallow Ground Water (3.3- to 4.3-m depth) (µg/L)	Deep-Soil Vapor (3-m depth) (µg/m³)	Middepth-Soil Vapor (2-m depth) (µg/m³)	Shallow-Soil Vapor (1-m depth) (µg/m³)	Subslab Vapor (2-m depth) (µg/m³)	Basement Air (µg/m³)	Ground Floor Air (µg/m³)	Outdoor Air (µg/m³)
Building #73 and location VP-9	Benzene	6400	12,000	660,000	250,000	<1600	<1000	<8	<2	<1.6
	Toluene	150,000	43,000	1,100,000	580,000	1000	<1000	<10	46	<1.9
	Ethylbenzene	56,000	3500	<150,000	<67,000	<2000	<1000	<11	11	<2.2
	Xylenes (total)	360,000	24,000	<150,000	<67,000	<2000	<1000	<24	57	<4.5
	MTBE	18,000	590,000	5,900,000	1,700,000	53,000	18,000	130	52	<1.8
	2,2,4-Trimethylpentane	NM	NM	1,900,000	1,000,000	10,000	96,000	700	160	<2.4
	Cyclohexane	39,000	<25,000	1,100,000	530,000		15,000	130	26	<1.8
	Oxygen	NM	NM	<1[2]	1.3[2]	9.3[2]	NM	NM	NM	NM
Building #63 and location VP-13	Benzene	<3.6	7500	390,000	NM	NM	<30	NM[3]	<2	NM
	Toluene	<18	14,000	540,000	NM	NM	<40	NM[3]	3.2	NM
	Ethylbenzene	<14	4200	<67,000	NM	NM	<40	NM[3]	<2	NM
	Xylenes (total)	<18	20,000	<160,000	NM	NM	<100	NM[3]	<5	NM
	MTBE	63	190,000	444,700	NM	NM	2.6	NM[3]	2.8	NM
	2,2,4-Trimethylpentane	NM	NM	2,400,000	NM	NM	<50	NM[3]	<2	NM
	Cyclohexane	<18	<5000	710,000	NM	NM	<40	NM[3]	<2	NM
	Oxygen	NM	0.63[4]	0.4[2]	NM	NM	NM	NM[3]	NM	NM
Building #14 and location VP-10	Benzene	NM	6000	<2100	69	<8	<3	<2	<2	NM
	Toluene	NM	<12,000	3300	890	43	36	13	9.3	NM
	Ethylbenzene	NM	2200	<2800	270	14	15	5.4	3	NM
	Xylenes (total)	NM	3300	<5700	1200	72	75	27	17	NM
	MTBE	NM	310,000	56,000	320	18	<4	<2	<2	NM
	2,2,4-Trimethylpentane	NM	NM	1700	720	77	<5	<2	<2	NM
	Cyclohexane	NM	<12,000	<2300	160	26	<4	<2	<2	NM
	Oxygen	NM	0.43[4]	NM	NM	NM	NM	NM	NM	NM
Building #18 and locations VP-11 and VP-12	Benzene	NM	100; 27	9.2; <9.2	NM	NM	2.1	3.9	3	NM
	Toluene	NM	<50; <25	13; 12	NM	NM	38	34	21	NM
	Ethylbenzene	NM	<40; <20	<12; 12	NM	NM	18	5.8	4.1	NM
	Xylenes (total)	NM	<50; <25	<26; <37	NM	NM	94	25	18	NM
	MTBE	NM	1300; 370	<10; <10	NM	NM	5.2	9.6	5.2	NM
	2,2,4-Trimethylpentane	NM	NM	31; 46	NM	NM	5.3	11	4.5	NM
	Cyclohexane	NM	<50; <25	<9.9; <9.9	NM	NM	<2	<2	<2	NM
	Oxygen	NM	2.3, 2.0[4]	20.3[2]	NM	NM	NM	NM	NM	NM
Building #22 and location VP-12	Benzene	NM	27	<9.2	NM	NM	<2[5]	NM[3]	<2	<1.6
	Toluene	NM	<25	12	NM	NM	5.0[5]	NM[3]	14	3.9
	Ethylbenzene	NM	<20	<12	NM	NM	<2[5]	NM[3]	<2	<2.2
	Xylenes (total)	NM	<25	<37	NM	NM	9.2[5]	NM[3]	11	4.5
	MTBE	NM	370	<10	NM	NM	2.3[5]	NM[3]	<2	<3.7
	2,2,4-Trimethylpentane	NM	NM	46	NM	NM	<2[5]	NM[3]	<2	<2.4
	Cyclohexane	NM	<25	<9.9	NM	NM	<2[5]	NM[3]	<2	<1.8
	Oxygen	NM	2.0[4]	19.8[2]	NM	NM	NM	NM[3]	NM	NM

NM = not measured.
[1] Results shown as "<XX" were nondetects; "XX" represents the detection limit for that sample.
[2] Percent.
[3] Building does not have a basement.
[4] mg/L.
[5] Crawlspace.

a low oxygen environment (dissolved oxygen levels of 0.4 to 2.3 mg/L, Table 2), with the lower oxygen concentrations located nearer to the contamination source.

Outdoor air samples indicated undetectable levels of benzene, ethylbenzene, MTBE, 2,2,4-trimethylpentane, and cyclohexane (Table 2). Detection limits for benzene and ethylbenzene (~2 $\mu g/m^3$) were at or above commonly observed outdoor concentrations recently reported by Sexton et al. (2004). Approximately 4 $\mu g/m^3$ of toluene and xylene were detected outside of building #22 but not at building #73. Sexton et al. reported median outdoor concentrations of these two chemicals of 2 to 3 $\mu g/m^3$. Elevated outdoor concentrations of these chemicals were not expected because Stafford Township is bounded on the east by the Atlantic Ocean and on the west by the Pine Barrens, a 30-mile-wide region of undeveloped land. Also, the gas station responsible for the ground water contamination had ceased operations prior to this study, so it did not represent a local above ground source of gasoline vapors.

The Use of Gasoline Tracers

2,2,4-Trimethylpentane (isooctane) and MTBE are chemicals added to gasoline to achieve desirable performance and environmental characteristics and do not have other common sources (Hazardous Substances Databank 2004). This contrasts with the BTEX chemicals, which are commonly reported in indoor air and may have various sources. The appearance of gasoline-specific chemicals indoors may therefore serve as an indication that the indoor air has been impacted by gasoline. A decreasing sequence of concentrations between the ground water and the indoor air for these chemicals may yield further evidence that the source of indoor air contamination is gasoline-contaminated ground water, as opposed to gasoline vapors from other sources (e.g., outdoors or an attached garage). For this reason, 2,2,4-trimethylpentane results were added to those normally investigated. Results for cyclohexane are also reported in this study. Although perhaps less useful as a tracer chemical due to other potential indoor sources, it was included because it was another gasoline constituent observed at significant levels in this study.

Concentration Patterns—Building #73

Concentrations of benzene, toluene, xylene, and MTBE in ground water adjacent to building #73 were above 10 mg/L, with a very high concentration for MTBE (590 mg/L, Table 2). Deep-soil vapor measurements at VP-9 (just above the water table, 3-m depth) for toluene, MTBE, 2,2,4-trimethylpentane, and cyclohexane were in excess of 1 million $\mu g/m^3$, with the highest observed concentration again being that for MTBE (5.9 × 10^6 $\mu g/m^3$). The benzene concentration was slightly lower (660,000 $\mu g/m^3$). Middepth-soil vapor measurements (at 2-m depth) remained high, although they were reduced relative to the deep-soil vapor concentration by 50% to 70%. Shallow-soil vapor samples (at 1-m depth) showed significantly lower concentrations, although they were still at or above 10,000 $\mu g/m^3$ for cyclohexane and 2,2,4-trimethylpentane. Of the BTEX chemicals, only toluene was confirmed (1000 $\mu g/m^3$). Oxygen levels were <1.0% at the deep vapor sampling

point, 0.9% to 1.6% at middepth, and 8% to 10% at shallow depth. It has been reported that oxygen levels above 4% are adequate for substantial degradation of BTEX chemicals to occur with a short distance in the vadose zone (DeVaull et al. 1997). Therefore, degradation of BTEX chemicals likely occurred between the middepth and the shallow sampling points at this location. MTBE degrades more slowly than the BTEX chemicals (Squillace et al. 1997), and the information available for 2,2,4-trimethylpentane and cyclohexane also suggest limited biodegradation potential (Hazardous Substances Databank 2004). Attenuation of these chemicals as they pass through the vadose zone would therefore be less than for the BTEX compounds. This behavior was observed for cyclohexane and 2,2,4-trimethylpentane, which showed less attenuation in the vadose zone than benzene and toluene, particularly in the upper oxygenated region of the soil column (Figure 2). However, attenuation of MTBE was greater than for any of the four hydrocarbon chemicals (Figure 2). While the reason for this is unclear, MTBE has a higher water solubility and a lower Henry's law constant relative to the other contaminants. While no rainfall fell within 2 d prior to soil vapor sampling, 4.2 cm of precipitation occurred 3 d prior to sampling. Partitioning of MTBE into infiltrating soil moisture may have caused a temporary reduction in the near-surface MTBE vapor concentrations.

Subslab concentrations of MTBE, 2,2,4-trimethylpentane, and cyclohexane were considerably lower than middepth-soil vapor concentrations adjacent to building #73, even though both these samples were taken at a similar depth (2 m). Two possible explanations exist. First, the ground water plume was small and concentrations may have decreased between the middepth-soil vapor sample and the subslab sampling location, which was 5 m away. Second, it is frequently assumed that under the influence of negative pressure inside of a building, a zone of influence exists around the building foundation (Little et al. 1992). When
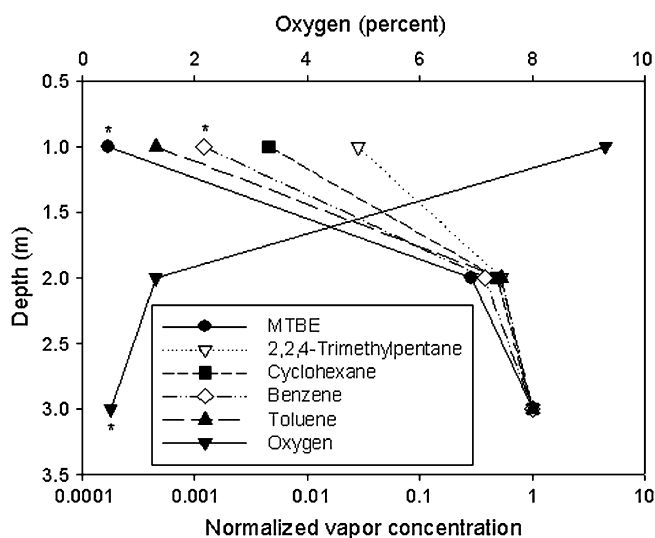
Figure 2. Vapor concentrations at location VP-9. Top axis is scale for oxygen measurements; bottom axis is normalized vapor concentration for remaining chemicals. Points marked with "*" were undetected and set at half the detection limit.

chemicals enter this zone, they are rapidly swept through the building foundation via soil-gas convection. Pressure measurements at this building indicated a slight depressurization relative to the exterior (-0.6 Pa), so convection may have been occurring. The dilution caused by convection could reduce subslab soil-gas concentrations relative to those measured adjacent to the building at a similar depth. BTEX chemicals were not detected in the subslab vapor, even though benzene and toluene were measured at substantial levels in the middepth-soil vapor sample. Degradation of these chemicals may have been occurring in the subslab soil zone, due to access of this area to oxygen from openings in the slab. Alternatively, the building's zone of influence may promote oxygen convection from the exterior soil surface to the subslab.

Measurable levels of MTBE, 2,2,4-trimethylpentane, and cyclohexane were found both in the basement air and at reduced levels in the ground floor in building #73. The appearance of the first two chemicals indoors suggested that the indoor air was impacted by gasoline vapors. The sequence of decreasing concentrations of these chemicals in the ground water, deep-soil vapor, middepth-soil vapor, subslab vapor, and indoor air, indicates that the likely source of these indoor contaminants was the ground water. The decrease in concentrations observed between the basement and the first floor is also compatible with a subsurface source since the first floor is further removed from the source and its air exchange would combine a portion of the basement air with additional outside air. Further evidence of a subsurface gasoline source was the presence of elevated levels of degradation-resistant MTBE, 2,2,4-trimethylpentane, and cyclohexane in the basement relative to the degradable BTEX compounds. An indoor gasoline source would have also yielded significant BTEX concentrations in the basement.

While BTEX concentrations in the basement were low, significant levels of toluene, ethylbenzene, and xylene were observed in the ground floor (Table 2). This building functioned as an antique shop, so contribution of chemicals from refinished furniture and related chemical storage was a distinct possibility. Indoor background concentrations of BTEX chemicals have been reported to be as high as those measured in building #73 (U.S. EPA 1987; Clayton et al. 1999; Edwards et al. 2001; Sexton et al. 2004). Results from the recent study by Sexton et al. (288 indoor air samples in the Minneapolis/St. Paul metropolitan area) give the following 10th to 90th percentile concentration ranges for the BTEX chemicals, in micrograms per cubic meter: benzene, 0.8 to 15.3; toluene, 2.4 to 53.8; ethylbenzene, 0.5 to 8.9; xylene, 2.2 to 48. The ethylbenzene and xylene concentrations in building #73 slightly exceed these ranges. However, they are below 90th percentile concentrations reported in the total exposure assessment methodology study (U.S. EPA 1987), which ranged up to 27 and 100 $\mu g/m^3$ for ethylbenzene and xylene, respectively (786 indoor air samples in New Jersey and California).

Consideration of available indoor data on the other gasoline-related contaminants was also useful. While indoor levels of 2,2,4-trimethylpentane could not be located in the literature, some data are available for the remaining two contaminants. Edwards et al. (2001) reported

that indoor cyclohexane concentrations measured in Helsinki, Finland (183 samples), were below the detection limit 80% of the time (<2 $\mu g/m^3$) and the 90th percentile concentration was 2.73 $\mu g/m^3$. In a survey of existing data, Brown et al. (1994) reported mean indoor air cyclohexane concentrations in various buildings of between 1 and 5 $\mu g/m^3$. The basement and indoor air concentrations measured in building #73 were considerably higher than these values (130 and 26 $\mu g/m^3$, respectively). Information on indoor levels of MTBE (100 homes in Elizabeth, New Jersey) suggests a median value of 6 $\mu g/m^3$ (Weisel 2002). This concentration is considerably lower than the levels measured in building #73 (52 to 130 $\mu g/m^3$). The indoor concentrations of cyclohexane, MTBE, and 2,2,4-trimethylpentane are sufficiently elevated in this building to suggest a subsurface source.

Concentration Patterns—Other Buildings

The ground water underlying buildings #63 and #14 also contained milligrams per liter concentrations of gasoline constituents, although lower than those for building #73 (Table 2). The deep-soil vapor adjacent to building #63 also exhibited high concentrations of contaminants; however, subslab and indoor air concentrations were low. Degradation or attenuation of chemicals during transport was apparently adequate to eliminate the potential for indoor air impacts. This building consisted of a slab-on-grade construction, so the transport distance in this case was 3.3 m, twice the distance for building #73. The deep-soil vapor adjacent to building #14 exhibited >1000 $\mu g/m^3$ for toluene, MTBE, and 2,2,4-trimethylpentane, and in the middepth-soil vapor sample, several hundred micrograms per cubic meter were measured for MTBE, 2,2,4-trimethylpentane, cyclohexane, and all BTEX chemicals except benzene. However, relatively low concentrations in the shallow-soil vapor, subslab, basement, and indoor samples were observed. This building exhibited an average depressurization of -4.1 Pa, which, as explained previously, could result in lowered subslab concentrations relative to middepth-soil vapor concentrations. MTBE, 2,2,4-trimethylpentane, and cyclohexane were not detected indoors, suggesting a lack of gasoline impacts. The BTEX chemical concentrations, although low, did show a decreasing trend between the subslab vapor, basement air, and ground floor air concentrations. However, the differences between the subslab and the basement concentrations were not large enough to suggest vapor intrusion because a minimum 10-fold decrease would be expected (U.S. EPA 2002). Furthermore, indoor concentrations were not above levels commonly observed due to other sources.

Buildings #18 and #22 were over relatively low contaminant concentrations in the ground water. Measurable levels of many of the studied chemicals were found indoors and in the subslab samples (Table 2). However, the observed indoor concentrations were not above commonly observed levels, and some of the contaminants were measured at higher levels indoors than in the subslab vapor. This suggests that the sources of these chemicals were not from the subsurface. All buildings in this study stored some cleaners or solvents indoors, which could have been sources

of some of these chemicals. Other factors potentially contributing to VOC levels in building #18 were recent painting and heavy smoking by an occupant of the building.

Contaminant Attenuation near the Water Table

When calculating ground water screening levels for the vapor intrusion pathway, the contaminant concentration in soil vapor at the base of the capillary fringe is estimated from the ground water concentration using the Henry's law constant and assuming equilibrium partitioning (U.S. EPA 2003). Measured contaminant concentrations in deep-soil vapor should always be less than the estimated concentration as a result of contaminant attenuation through the capillary transition zone and possible nonequilibrium conditions for partitioning. This was confirmed in the present study, where measured concentrations in deep-soil vapor were frequently <1% of the concentrations predicted at the base of the capillary fringe (Table 3). At well locations that exhibited evidence of residual NAPL near the water table (VP-9 and VP-13), the measured concentrations in soil vapor were often between 10% and 50% of predicted concentrations. Higher percentages would be expected at these locations since residual NAPL was likely present above the water table. In addition, Raoult's law may be a more applicable model than Henry's law for prediction of vapor concentrations where NAPL is present.

Attenuation Factors

The attenuation factor may be defined as the ratio of the indoor air concentration to a source soil-gas concentration at a specified location (Johnson and Ettinger 1991). When the source location is the ground water, the ground water concentration may be converted to an equivalent equilibrium soil-gas concentration using the Henry's law constant. When predicting indoor air concentrations from measured ground water concentrations in the absence of site-specific data, the U.S. EPA recommends using a generic attenuation factor of 1×10^{-3} to determine whether a particular location requires further investigation (U.S. EPA 2002). The generic factor was developed by studying the distribution of experimentally determined attenuation factors from past site investigations and selecting a value that was protective for 95% of the residences studied. The factor is also compatible with theoretical predictions from the Johnson and Ettinger model (U.S. EPA 2003; Johnson and Ettinger 1991), when run using conservative assumptions (sand soil, shallow depth to water table, and no degradation). More typical attenuation factors between the indoor air and the ground water have been observed to be in the range of 10^{-3} to 10^{-6} for nondegrading chlorinated compounds and 10^{-4} to 10^{-7} for degradable BTEX compounds (U.S. EPA 2002; Hers et al. 2003). The Johnson and Ettinger model also predicts lower attenuation factors when less-conservative assumptions are used (Johnson et al. 1999).

One of the five buildings studied (building #73) yielded sampling results for MTBE, cyclohexane, and 2,2,4-trimethylpentane that clearly indicated that there were indoor air impacts from gasoline-contaminated ground water. For this location, attenuation factors were calculated between various sampling points and the indoor

Table 3
Contaminant Attenuation near the Water Table

Location		Concentration in Shallow Ground Water (3.3- to 4.3-m depth) (µg/L)	Predicted Concentration in Vapor at Base of Capillary Fringe (µg/m³)	Measured Concentration in Deep-Soil Vapor at 3-m Depth (µg/m³)	Concentration Ratio, Deep-Soil Vapor/Base of Capillary Fringe
VP-9	Benzene	12,000	1,920,000	660,000	0.34
	Toluene	43,000	7,826,000	1,100,000	0.14
	Ethylbenzene	3500	724,500	<150,000	<0.21
	Xylenes (total)	24,000	4,200,000	<150,000	<0.04
	MTBE	590,000	11,033,000	5,900,000	0.53
VP-13	Benzene	7500	1,200,000	390,000	0.32
	Toluene	14,000	2,548,000	540,000	0.21
	Ethylbenzene	4200	869,400	<67,000	<0.08
	Xylenes (total)	20,000	3,500,000	<160,000	<0.04
	MTBE	190,000	3,553,000	444,700	0.12
VP-10	Benzene	6000	960,000	<2100	<0.002
	Ethylbenzene	2200	455,400	<2800	<0.006
	Xylenes (total)	3300	577,500	<5700	<0.01
	MTBE	310,000	5,797,000	56,000	0.01
VP-11	Benzene	100	16,000	9.2	<0.0006
	MTBE	1300	24,310	<10	<0.0004
VP-12	Benzene	27	4320	<9.2	<0.002
	MTBE	370	6919	<10	<0.001

Note: Henry's law constants (17°C)—benzene, 0.160; toluene, 0.182; ethylbenzene, 0.207; xylenes, 0.175 (average); MTBE, 0.0187.

air (Table 4). For the BTEX chemicals, the values reported are maximum due to some indoor air measurements being below quantifiable limits and because of potential contribution from indoor air sources. For MTBE, cyclohexane, and 2,2,4-trimethylpentane, indoor concentrations were sufficiently elevated that any contribution by background indoor sources would not have been significant. The attenuation factor between the ground water and the indoor air was $<1.5 \times 10^{-5}$ for ethylbenzene, $<6 \times 10^{-6}$ for xylene and benzene, and $<1.2 \times 10^{-6}$ for toluene (Table 4). The Johnson and Ettinger model (version 3.0 spreadsheets, U.S. EPA 2003) was run for building #73, assuming the U.S. EPA draft vapor intrusion guidance–recommended default values of 0.25/h for the building air exchange rate, 5 L/min for the soil-gas entry rate, and a building mixing volume of 366 m^3 (U.S. EPA 2002). A measured value for soil total porosity (0.38) and an estimated value for soil vadose zone water-filled porosity (0.028 v/v) were used. Consistent with the U.S. EPA (2003) approach, the water-filled porosity was estimated as the midpoint between the measured field capacity and the measured residual water saturation. The capillary zone height (17 cm) and capillary zone moisture content, 0.253 (v/v), were estimated values (U.S. EPA 2003). Attenuation factors for the BTEX chemicals (in the absence of degradation) ranged from 1.1 to 1.2×10^{-3}, which are much higher than the observed values. Since building #73 exhibited only slight depressurization (0.6 Pa) and was of older construction, a less-conservative simulation was also conducted using a lower soil-gas entry rate (1 L/min) and a higher building exchange rate (1/h). A higher generic vadose zone soil moisture content for sand was also used (0.054 v/v, U.S. EPA 2002). These simulations yielded attenuation factors for the BTEX chemicals an order of magnitude lower (1.2 to 1.3×10^{-4}). Since observed attenuation factors were still one to two orders of magnitude lower than these values, and elevated oxygen levels were observed above 2-m depth, it suggests that degradation of these chemicals was occurring in the vadose zone.

A quantitative ground water to indoor air attenuation factor could be calculated for MTBE since concentrations in both compartments were above the reporting limit. The attenuation factor for this chemical, as well as those for cyclohexane and 2,2,4-trimethylpentane, may be more representative of vapor transport conditions in the absence of biodegradation. As expected, the observed value for MTBE (1.2×10^{-5}) was higher than those for the BTEX compounds. However, it was still in the lower 25th percentile of observed values reported by the U.S. EPA (U.S. EPA 2002) and considerably less than the generic attenuation factor (1×10^{-3}), despite the presence of sand soil and a short transport distance to ground water. Possible reasons for the low measured attenuation factor at building #73 include (1) reduced soil-gas entry rate due to relatively low building depressurization; 2) a relatively high building air exchange rate; (3) elevated moisture in the vadose zone or capillary zone; or (4) nonequilibrium partitioning between the ground water and the soil vapor at the base of the capillary fringe.

The U.S. EPA generic (conservative) attenuation factor for nondegradable compounds between the basement air and the deep-soil vapor is 1×10^{-2}. For benzene and toluene, the measured soil vapor attenuation factors for building #73 were $<10^{-5}$ (Table 4). As aforementioned, degradation of these chemicals is likely a factor. Soil vapor attenuation factors for MTBE, 2,2,4-trimethylpentane, and cyclohexane were somewhat higher (between 3.6×10^{-4} and 2.2×10^{-5}). Attenuation factors between the basement air and the subslab vapor were 7.2×10^{-3} to 8.4×10^{-3} for cyclohexane, 2,2,4-trimethylpentane, and MTBE (Table 4). While lower than the conservative subslab attenuation factor assumed by the U.S. EPA in their soil screening guidance (85th percentile value of 1×10^{-1}), these values are very near the 50th percentile values for this parameter reported in the U.S. EPA vapor intrusion guidance for Lowry Air Force Base. Again, the relatively low depressurization observed for building #73 may have reduced soil-gas entry and thus the measured attenuation factor.

Attenuation factors between the ground floor and the basement of building #73 for cyclohexane, MTBE and 2,2,4-trimethylpentane were between 0.2 and 0.4. This result provides additional evidence for subsurface sources of these contaminants and also indicates the relative level of air exchange between the two floors.

Table 4
Attenuation Coefficients between Exterior and Interior Concentrations
Building #73 in Stafford Township, New Jersey

	Basement/Ground Water	Basement/Deep-Soil Vapor	Basement/Subslab	Ground Floor/Basement
Benzene	$<4.3 \times 10^{-6}$	$<1.2 \times 10^{-5}$	ND	ND
Toluene	$<1.2 \times 10^{-6}$	$<8.6 \times 10^{-6}$	ND	ND
Ethylbenzene	$<1.5 \times 10^{-5}$	ND	ND	ND
Xylenes (total)	$<5.7 \times 10^{-6}$	ND	ND	ND
MTBE	1.2×10^{-5}	2.2×10^{-5}	7.2×10^{-3}	3.9×10^{-1}
2,2,4-Trimethylpentane	NM	3.6×10^{-4}	7.2×10^{-3}	2.3×10^{-1}
Cyclohexane	ND	1.2×10^{-4}	8.4×10^{-3}	2.1×10^{-1}
EPA generic factor	1×10^{-3}	$1E \times 10^{-2}$	1×10^{-1}	

ND = not determined because source concentration below quantifiable levels; NM = not measured in ground water.

Temporal Variability of Measured Concentrations

The work conducted at Stafford Township was limited to one round of sampling in October 2002, after 2 months of relatively normal weather conditions. No significant weather events occurred immediately prior to or during the sampling time period. Therefore, the concentrations observed were expected to be reasonably representative for the time of year sampled. The variation with time of soil vapor concentrations and indoor air concentrations at this site is not known. Short-term fluctuations in measured concentrations may be caused by weather events and changes in building air exchange rates due to opening of windows and the use of heating and air-conditioning systems (Hers et al. 2001). Seasonal variations in water table heights and soil moisture may also affect the vapor intrusion measurements. To obtain better estimates of this variability, measurements taken at several times during the year would be recommended.

Conclusions

The potential for chemical vapor intrusion from gasoline-contaminated ground water to the interior of homes was studied at a site in Stafford Township, New Jersey. While measurable levels of BTEX chemicals were observed indoors in all the buildings studied, only one of them (building #73) was found to exhibit indoor air impacts attributable to the gasoline, and these impacts were limited to MTBE, 2,2,4-trimethylpentane, and cyclohexane. This conclusion was based on consideration of several lines of evidence, including (1) vapor attenuation patterns between the contaminant source and the indoor air; (2) observation of indoor concentrations that were significantly higher than background indoor or outdoor levels commonly reported in the literature, or in adjacent buildings; (3) the lack of observed indoor sources of gasoline; and (4) elevated indoor levels of the aforementioned three chemicals relative to the BTEX chemicals. Data on indoor concentrations of MTBE are scarce, but based on the results of this study, this chemical was found to be a potential indoor air contaminant from gasoline-contaminated ground water, although only at high milligrams per liter levels. Measured attenuation factors for all chemicals studied at Stafford Township were one to three orders of magnitude lower than U.S. EPA default factors, even though the site exhibited conditions favorable to vapor intrusion. Finally, while interpretation of measured indoor BTEX concentrations is often difficult due to multiple possible sources, the analysis of tracer chemicals associated mainly with gasoline (MTBE and 2,2,4-trimethylpentane) can help confirm indoor impacts from this contaminant.

Acknowledgments

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