Characterizing TCE Exposure Distribution for Occupants of Houses with Basements

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ABSTRACT

When characterizing the exposure to subsurface contaminants via vapor intrusion, it is often assumed that the indoor air within a house is well mixed. However, this assumption might not be valid for houses with basements. Data from a small number of basement ventilation experiments show that there is limited air exchange between the basement and the rest of the house, which means that contaminant concentrations in the basement are elevated relative to the rest of the house. As a result, occupants' exposure to the subsurface contaminant would vary depending on their time spent in the basement. We applied the two-compartment modeling approach suggested by Olson and Corsi (2001) to a group of 13 single-family houses situated above a trichloroethene (TCE) groundwater plume. TCE concentrations were monitored inside these houses every 2 months for 1 year. A few indoor air samples were collected in the basement, while others were collected in the first floor of the house. In addition, TCE concentrations were also monitored in the outdoor air, sub-slab soil gas, and groundwater. We characterized the basement air exchange and time spent in the basement for a typical (median) and high-exposure (95th percentile) case. Data from the National Human Activity Pattern Survey provides the fraction of time spent in basements based on recall diaries. Using the two-compartment model, we then estimated the exposure distribution for occupants residing in houses with a basement. The exposure predictions were compared to the conservative assumption that the measured TCE concentrations in the basement are representative throughout the whole house. Over- or under-predicting the exposure concentrations may affect the conclusions of a risk assessment if the initial estimate is near the "acceptable" risk level. This analysis characterizes two important parameters used to evaluate exposure to elevated TCE concentrations in the basement.

Key words: vapor intrusion, indoor air modeling, basement air flow, air-exchange rate, exposure assessment

INTRODUCTION

TCE Vapor Intrusion Sampling Data

Trichloroethene (TCE) was detected in the groundwater at the former Lowry Air Force Base (AFB)[1] near Denver, Colorado. An investigation was conducted to determine whether occupants of off-base residences overlying the main TCE groundwater plume are exposed to unacceptable inhalation health risk. Sampling was conducted in 13 homes at two-month intervals between March 2000 and February 2001.[2] Samples collected include indoor air, outdoor air, basement air, crawlspace air, sub-slab soil gas, and groundwater. Besides TCE, other volatile organic compounds (VOCs) such as tetrachloroethene (PCE) and 1,1,1-trichloroethane (1,1,1-TCA), were also analyzed. The investigation found that TCE was the most often detected compound and was detected in the highest concentrations in the substructure samples; therefore, it was most likely to be the primary chemical detected in indoor air samples due to vapor intrusion. The next two most commonly detected VOCs were PCE and 1,1,1-TCA. However, comparison of the indoor air concentrations with groundwater and outdoor air concentrations suggests the presence of a non-groundwater source of PCE and 1,1,1-TCA. Therefore, this paper focuses on TCE only and assumes that groundwater is the predominant source to indoor air.

Twelve of the 13 residences sampled are single-family detached homes with either a basement or crawlspace. TCE vapors from the subsurface to indoor air must first pass through the basement foundation, or through the crawlspace, before entering into the building. While the crawlspace is not an occupied area, residents can be exposed to higher concentrations of TCE while in the basement. One conservative method of assessing exposure is to collect indoor air samples in the basement. However, this approach might be too conservative if the basement is used only infrequently or for a short duration, such as a laundry room. Olsen and Corsi[3] proposed a two-compartment model to describe the migration of soil gas into the basement, and the air exchange between the basement and the reminder of the house. Instead of relying on basement-only or ground-floor-only concentrations to evaluate TCE exposure for the Lowry AFB residences, we applied this two-compartment model to estimate exposure. This allows us to consider the implications of higher TCE concentrations in the basement where residents might be exposed for different time durations.

Eight residences (#3, #4, #18, #21, #22, #23, #24, and #28) at the Lowry AFB have a basement. Sub-slab soil gas samples were collected from these residences, with one exception at residence #28, where basement air was sampled instead. The other four residences (#2, #5, #25, and #26) have a crawlspace, where crawlspace air samples were collected. Indoor air samples were also collected from the first floor of the residences concurrently. There were two exceptions where the indoor air samples were collected from the basement instead of the first floor of the residences because the basements at these residences were fully finished (#3 and #22). Figures 1–3 show the indoor air, basement/crawlspace air, and sub-slab soil gas TCE concentrations collected at these 12 residences.

The average and range of TCE concentrations measured are summarized in Table 1. Indoor air, basement air, and crawlspace air were all 24-hour canister samples analyzed using EPA Method TO-15. Sub-slab soil gas samples were collected after approximately 2 liters of air was purged. Anomalous soil gas data were reported on one occasion each at residences #3 (December 2000), #22 (May 2000), and #23 (December 2000), where the measured concentrations were at least two orders of magnitude lower than other sampling periods. These values were excluded from Table 1. TCE concentrations in outdoor air were also measured near three of the residences, and were lower (0.1 $\mu g/m^3$ on average, ranging from 0.036 to 0.39 $\mu g/m^3$) than concentrations measured inside the residences.

Table 1. Average TCE concentrations (μg/m³) and concentration ranges

	Indoor Air	Basement/ Crawlspace Air	Sub-Slab Soil Gas
February 2000	2.3 (0.2–11)	11.1 (1.8–20)	1968 (260–5400)
May 2000	1.2 (0.1–7.7)	6.0 (1.8–14)	1545 (230–4000)
August 2000	0.2 (0.1–0.5)	4.4 (0.4–14)	2800 (240–10000)
October 2000	0.9 (0.3–1.8)	5.4 (2.2–10)	2743 (130–6600)
December 2000	3.2 (0.3–9)	13.1 (2.6–38)	2060 (140–5100)
February 2001	4.0 (0.7–12)	14.9 (3.7–51)	2153 (130–5200)

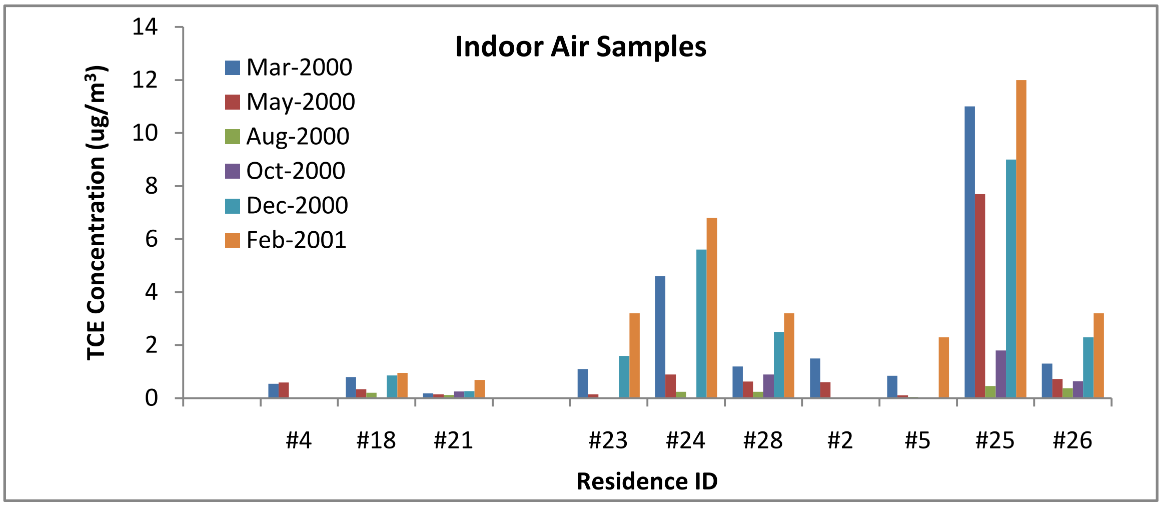

Figure 1. TCE concentrations measured in the indoor air of residences at Lowry Air Force Base.

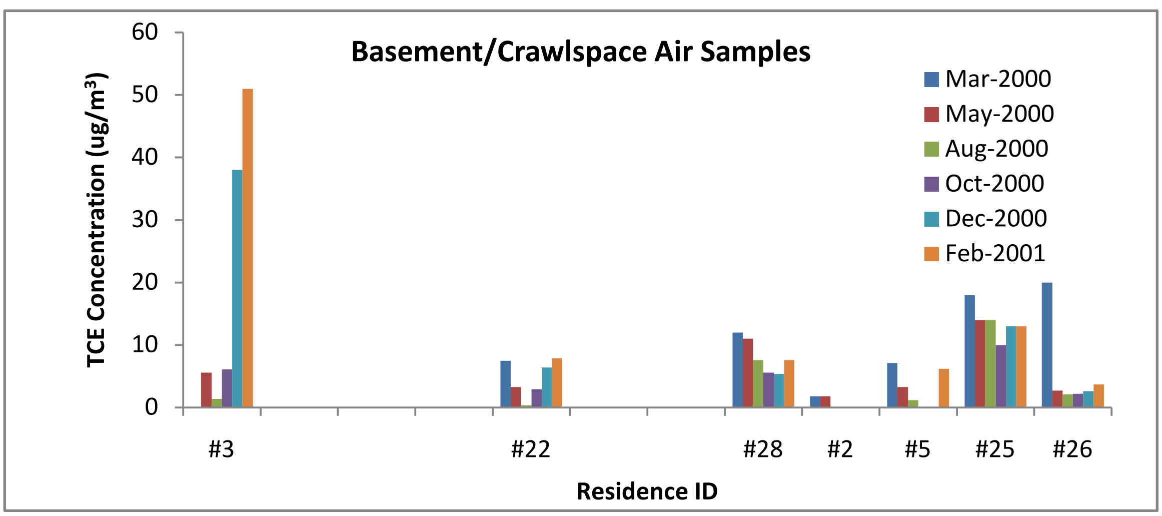

Figure 2. TCE concentrations measured in basement air (residences #3, #22, and #28) and in crawlspace air (#2, #5, #25, #26).

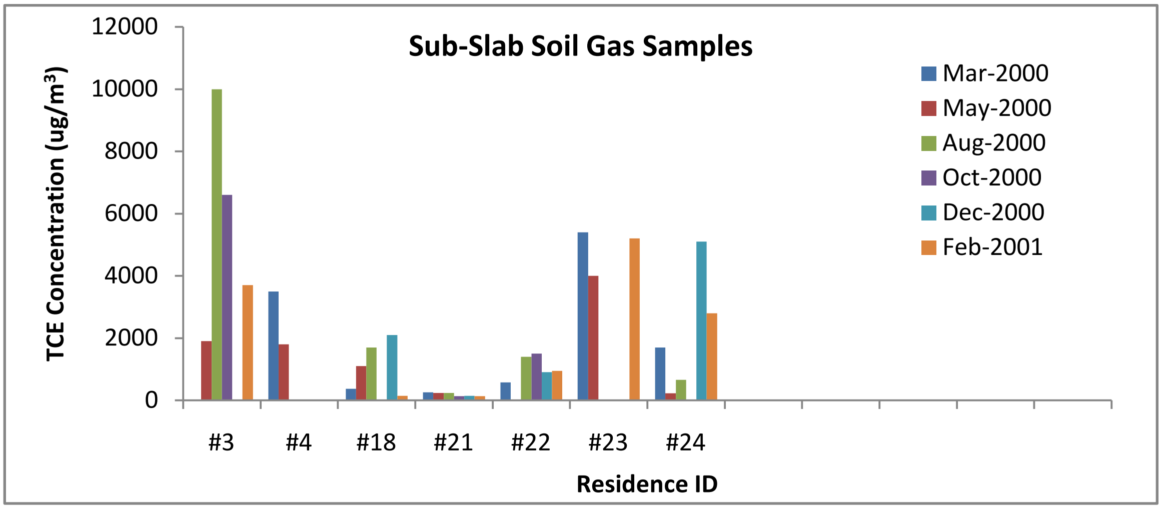

Figure 3. TCE concentrations measured in the sub-slab soil gas of residences with a basement.

DATA ANALYSIS METHODS

Two-Compartment Model

Olsen and Corsi[3] proposed a simplified two-compartment model to describe the concentrations from vapor intrusion in the basement air, C_b (μg/m^3), and the remainder of the house, C_i (μg/m^3), at steady state:

Equation 1

$$C_b = \frac{E}{Q_b} \quad \text{and} \quad C_i = \frac{E}{Q_{out}}$$

where:

E (μg/h) is the migration rate of the chemical from soil to basement

Q_b (m^3/h) is the volumetric air flow from the basement to the ground floor

Q_{out} (m^3/h) is the volumetric air flow from the house to the outdoors

Equation 1 assumes that a negligible amount of chemical enters the ground floor of the house from the outdoors, and from the ground floor of the house to the basement. In other words, the model assumes that the predominant transport of chemicals from vapor intrusion is from the subsurface into the basement, and from the basement to the ground floor of the house. This simplified model further assumes that the infiltrated chemical in the basement is drawn predominantly to the ground floor of the house, and a very small fraction is lost through cross-ventilation in the basement. Equation 1 is therefore appropriate for houses that are located directly above a groundwater plume of contaminants, such as the residences being considered. In situations where these assumptions may not hold, other parameters such as the volumetric airflow from the ground floor to basement must also be estimated to calculate C_b and C_i.

Equation 1 implies that the ratio of chemical concentrations in the basement and ground floor, C_b/C_i, equals the ratio of ground floor-to-outdoor air flow and basement-to-ground floor air flow, Q_{out}/Q_b. Olsen and Corsi measured the basement air-exchange rate (Q_b divided by the basement volume) of a one-story house in Paulsboro, New Jersey, to range from 0.17 to 0.75 h^{-1}. However, the house air-exchange rate was not measured.

Boston Multi-Zonal Airflow Studies

Dodson et al.[4] measured the inter-zonal air flow as part of an indoor air quality assessment study in Boston, Massachusetts. Thirty-five of the residences sampled had basements, including both finished and unfinished. Air-flow rates from the basement to the occupied zone were measured over two seasons: summer 2004 and winter 2005. The authors found that the estimated air-flow rates between the basement and the occupied zone vary significantly ($p = 0.003$) by season, with a mean of 67 m^3/h in summer and 174 m^3/h in winter. They attributed this difference to a stronger stack effect in the winter within the residence. They also observed a significant ($p = 0.036$) negative correlation between the air-flow rates from the basement to the occupied zone and the temperature difference between the occupied zone and the basement in the summer. In winter, a marginally significant ($p = 0.071$) positive correlation was observed with respect to temperature difference.

The median percent of air-flow rate from the basement to the occupied zone ($Q_b/Q_{out} \times 100\%$) was 15% in summer and 48% in winter. This means that the ratio of Q_{out}/Q_b roughly equals 6.7 (1/15%) in summer and 2.1 (1/48%) in winter. Assuming that Equation 1 applies, if these Boston residences were subjected to vapor intrusion, contaminant concentrations in the basement air would be 6.7× the indoor air concentrations in the ground floor in summer. In winter, contaminant concentrations in the basement and ground floor of the residences are expected to be closer. The percent of air-flow rate from the basement to the occupied zone was variable among the residences sampled. The 5th to 95th percentile value ranged from 1% to 66% in summer, and 10% to 100% in winter. The ratio of C_b/C_i would therefore range from 1.5 to 100 in summer, and 1 to 10 in winter.

Ratio of C_b/C_i from Basement/Crawlspace Samples

The ratio of C_b/C_i, or Q_{out}/Q_b, is a measure of connectivity between the basement and the ground floor of the house. This ratio can also be interpreted as an attenuation factor of the infiltrated contaminants between the two compartments of the house. Differences in building construction could mean that the factors of 6.7 (summer) and 2.1 (winter) estimated above from the Boston samples may not be applicable to the residences at Lowry AFB. Alternatively, the ratio C_b/C_i can be calculated directly based on the TCE concentrations measured in the basement/crawlspace air relative to indoor air from a subset of the Lowry AFB residences. This method has the advantage that the data represent residences in the neighborhood built with similar construction methods.

Five of the Lowry AFB residences had both indoor air and basement/crawlspace air samples. Even though these five residences do not have a fully finished basement or a basement with formal flooring, they are still relevant data to consider because of the similar age and construction of the houses in the neighborhood. The TCE data for these houses are listed in Table 2. Residence #28 has a basement with dirt floor that is used only for storage**.** The remaining four of the five residences have a crawlspace rather than a basement. Crawlspaces can have significant cross-ventilation such that only a fraction of the infiltrated chemicals enter the ground floor of the house.[5] The same is true for well-ventilated basements, such as those with windows. In this case, the C_b/C_i ratios of the five residences are all within similar ranges (Table 2). This suggests that there is no significant difference in the attenuation of the infiltrated chemicals from the basement or crawlspace into the first floor of the house. This is likely because the residences were built with similar construction methods. In neighborhoods with more diverse construction, it is necessary to consider whether the available data are applicable to residences with different floor types.

Table 2. Calculated ratio C_b/C_i from Lowry AFB residences

	TCE Indoor Air Concentrations (μg/m^3)	**TCE Basement/Crawlspace Air Concentrations (μg/m^3)**	**Ratio C_b/C_i**	**Daily Average Outdoor Temperature (^{o}F)**
Residence #28 (w/basement)	1.2	12.0	10.0	62.8
	0.6	11.0	17.5	64.8
	0.2	7.6	31.7	74.6
	0.9	5.6	6.3	59.5
	2.5	5.4	2.2	28.7
	3.2	7.6	2.4	32.7
Residence #2 (w/crawlspace)	1.5	1.8	1.2	32.7
	0.6	1.8	3.0	68.0
Residence #5 (w/crawlspace)	0.8	7.1	8.5	52.8
	0.1	3.3	30.0	61.8
	0.1	1.2	22.6	72.1
	2.3	6.2	2.7	32.7
Residence #25 (w/crawlspace)	11.0	18.0	1.6	44.3
	7.7	14.0	1.8	61.8
	0.5	14.0	30.4	80.1
	1.8	10.0	5.6	59.5
	9.0	13.0	1.4	28.7
	12.0	13.0	1.1	26.9
Residence #26 (w/crawlspace)	1.3	20.0	15.4	52.3
	0.7	2.7	3.8	60.4
	0.4	2.1	5.5	74.0
	0.6	2.2	3.4	50.7
	2.3	2.6	1.1	27.1
	3.2	3.7	1.2	26.9

The average C_b/C_i categorized by the daily average outdoor temperature for the Lowry AFB residences is summarized in Table 3. The average C_b/C_i for these houses in winter is similar to the Boston study. The ratio from the Boston study was 2.1 in winter, which is roughly the same as that observed in the Lowry AFB residences (C_b/C_i = 1.7, see Table 3) with paired basement/crawlspace TCE concentrations. A larger C_b/C_i ratio is calculated in summer, based on the Lowry AFB residences as compared to the Boston study, likely because the sampling protocol allowed open windows and doors. Faster air exchange with the outdoors would lower the TCE concentrations indoors, and therefore resulted in a higher C_b/C_i ratio. Based on the fact that the Boston study found similar overall air-exchange rate in both seasons, windows and doors were likely kept closed throughout the study.

Table 3. Summary of calculated ratio C_b/C_i

	Ratio C_b/C_i		
Daily Average Outdoor Temperature	**Average**	**Min–Max**	**5^{th}–95^{th} Percentile**
>60 °F	15.6 (n = 10)	1.8–31.7	2.3–31.1
40–60 °F	6.8 (n = 6)	1.6–15.4	2.1–13.7
<40 °F	1.7 (n = 8)	1.1–2.7	1.1–2.6

MODEL PREDICTIONS

The National Human Activity Pattern Survey[6] (NHAPS) is a telephone survey (n = 9,368) of exposure-related human activities in the U.S. conducted from September 1992 through September 1994. The survey collected 24-hour retrospective diaries and answers to a number of questions related to exposure to air and water contaminants. Tsang and Klepeis (1998)[7] found generally good agreement between NHAPS representation and the 1990 U.S. census. All statistics presented below rely on the post-stratification weights that Klepeis et al. (1996)[6] have devised to correct for population proportions for age and sex.

According to NHAPS, about 35% of the U.S. population lives in a detached single-family house with a basement. Among this population, the median time spent at home is 15.4 hours per day (95^{th} percentile = 24 hours). However, only 8% of the NHAPS respondents reported spending time in the basement during the previous 24 hours. Among those who spent time in the basement, the median time spent was 1.5 hours (95^{th} percentile = 12 hours). The median fraction of time that a resident spends in the basement is 0.09 (95^{th} percentile = 0.42). This shows that it is highly conservative to assume that residents are exposed to chemicals in basement air from vapor intrusion for 24 hours per day.

Residences with Fully Finished Basements

Residences #3 and #22 both have a fully finished basement. The average TCE concentrations measured in the basements were 20.4 $\mu g/m^3$ and 4.7 $\mu g/m^3$, respectively. These would be the exposure concentrations if residents were to spend 24 hours a day in the basement. However, based on the NHAPS data, this is likely to be a very conservative assumption.

The ratio of C_b/C_i for each sampling day is correlated to the daily average outdoor temperature, as summarized in Table 3. This calculation uses the average C_b/C_i ratio (Table 3) to predict C_i based on the measured C_b value. Table 4 shows the estimated TCE concentrations for typical and high-end exposure scenarios when residents spend 9% and 42% of their time in the basement while at home. The typical estimated exposure concentrations are about 50% lower than estimates based on basement air measurements alone. Even in the high-end exposure scenario wherein residents spend close to half of their time in the basement, their estimated exposure is about 30% lower than estimates based on basement air measurements alone.

Table 4. TCE exposure concentration estimates for residences with fully finished basements (f = fraction of time spent in basement while at home)

Residence	Sample Date	Daily Average Outdoor Temperature (°F)	Ratio C_b/C_i	Measured C_b (µg/m³)	Predicted C_i (µg/m³)
#3	6/15/2000	72.9	15.6	5.6	0.4
	8/14/2000	79.6	15.6	1.4	0.1
	10/19/2000	59.5	6.8	6.1	0.9
	12/14/2000	27.3	1.7	38	23.0
	2/8/2001	13.7	1.7	51	30.8
	Estimated exposure concentration (µg/m³) =			20.4 (average)	11.9 (f = 0.09) 15.0 (f = 0.42)
#22	3/25/2000	50.3	6.8	7.5	1.1
	5/24/2000	64.8	15.6	3.3	0.2
	8/16/2000	74.6	15.6	0.37	0.02
	10/19/2000	59.5	6.8	2.9	0.4
	12/14/2000	27.3	1.7	6.4	3.9
	2/6/2001	32.7	1.7	7.9	4.8
	Estimated exposure concentration (µg/m³) =			4.7 (average)	2.0 (f = 0.09) 3.0 (f = 0.42)

Residences with Partially/Unfinished Basements

For residences with partially finished or unfinished basements near the Lowry AFB, indoor air samples were collected from the ground floor only. Such basements are sometimes used as laundry rooms. For example, washers and dryers were found in the basements of residences #21 and #23. NHAPS reports that 31% of the detached single-family houses with a basement store their washers and dryers in the basement. Elevated TCE concentrations in the basement could mean that exposure is underestimated if calculated based on the ground-floor indoor air measurements alone.

The ratio of C_b/C_i is applied to residences near Lowry AFB by reference to the daily average outdoor temperature relationship in Table 3. In this case, the measured parameter is C_i, and the prediction gives C_b. Only about 5% of the NHAPS respondents did laundry in the previous 24 hours. Because this percentage is low, only a few respondents (n = 57) provided data on how long they spent doing laundry. To increase the sample size, data from all single-family houses were included regardless of the location of the washing machine. This increases the same size to n = 352. Data from two survey questions were combined to give the fraction of time spent doing laundry while at home. The first question was the time a respondent spent doing laundry in the previous 24 hours. Among those who said yes, the median time spent doing laundry was 1 hour (95th percentile = 3 hours).

The second question was the frequency of using a washing machine to wash clothes. This question was asked on the exposure questionnaire portion (instead of the diary) of the NHAPS. There were two versions of the questionnaire, and this question was included on only one of them; therefore, data were available from only half the respondents. Table 5 shows the frequency of using a washing machine to wash clothes from all respondents who reside in single-family detached houses, and respondents who did laundry in the previous 24 hours of the survey. The fraction of time spent doing laundry while at home is calculated by the number of times the washing machine is used multiplied by the duration. The median fraction of time spent doing laundry while at home is 0.018 (95^{th} percentile = 0.096). These fractions are somewhat conservative, because the subgroup of respondents who did laundry in the past 24 hours of the survey tends to use the washing machine more often on a weekly basis, as shown in Table 5. For example, about one-third of the respondents who did laundry in the past 24 hours do laundry almost every day, whereas only 18% of all respondents report being in this category. This means that the fraction of time spent doing laundry by all respondents is likely to be lower than what is calculated here based on the subgroup data alone.

Table 5. NHAPS data on number of times washing machine is used to washing clothes

Number of Times Washing Machine is Used		Respondents who Did Laundry in Past 24 Hours Frequency (*n* = 162)	All Respondents Frequency (*n* = 2866)
Never or don't know	(*n* = 0.0)	2.1%	16.2%
Less than once a week	(*n* = 0.5)	3.0%	6.3%
One to two times a week	(*n* = 1.5)	30.1%	31.2%
Three to five times a week	(*n* = 4.0)	33.0%	27.9%
Almost every day	(*n* = 6.0)	31.4%	18.3%

Table 6 shows estimated exposure concentrations for a typical scenario wherein residents spend a small fraction of their time (f = 0.018) doing laundry in the basement while at home, and whether residents spend significantly more time on this activity (f = 0.096). The typical case roughly corresponds to doing laundry once a week for 2 hours, and the high-end exposure case corresponds to doing laundry almost daily for 2 hours. Residence #4 was excluded from this analysis because only two indoor air samples were collected in April and May of 2000. Instead of a quantitative calculation of exposure concentrations, it would be more appropriate to evaluate risk for this residence by also considering other lines of evidences that are beyond the scope of this analysis.

Compared to the average TCE concentrations measured in the ground floor of the residences, ignoring the exposure while doing laundry in the basement typically means a slight underprediction (5%). However, for residents who do laundry more frequently, the underprediction can reach 30%. This calculation assumes that residents spend the entire time in the basement while doing laundry, so it is a conservative estimate. On the other hand, the estimated exposure concentrations assume that no other activity takes place in the basement. Residents' exposure to TCE would be higher than estimated in Table 6 if the basements were used more extensively.

Table 6. TCE exposure concentration estimates for residences with partially/unfinished basement if used only for laundry
(f = fraction of time spent in basement while at home doing laundry)

Residence	**Sample Date**	**Daily Average Outdoor Temperature (°F)**	**Ratio C_b/C_i**	**Measured C_i (µg/m^3)**	**Predicted C_b (µg/m^3)**
#18	3/22/2000	32.7	1.7	0.80	1.3
	5/30/2000	68.0	15.6	0.34	5.3
	8/24/2000	69.3	15.6	0.21	3.3
	12/18/2000	28.7	1.7	0.86	1.4
	2/6/2001	32.7	1.7	0.96	1.6
	Estimated exposure concentration (µg/m^3) =			0.63 (average)	0.67 (f = 0.02) 0.82 (f = 0.10)
#21	3/23/2000	44.3	6.8	0.18	1.2
	5/25/2000	61.8	15.6	0.15	2.3
	8/14/2000	79.6	15.6	0.12	1.9
	10/26/2000	46.2	6.8	0.25	1.7
	12/18/2000	28.7	1.7	0.27	0.4
	2/6/2001	32.7	1.7	0.69	1.1
	Estimated exposure concentration (µg/m^3) =			0.28 (average)	0.30 (f = 0.02) 0.39 (f = 0.10)
#23	3/23/2000	44.3	6.8	1.1	7.5
	5/25/2000	61.8	15.6	0.14	2.2
	12/19/2000	32.7	1.7	1.6	2.6
	2/6/2001	32.7	1.7	3.2	5.3
	Estimated exposure concentration (µg/m^3) =			1.51 (average)	1.56 (f = 0.02) 1.79 (f = 0.10)
#24	3/23/2000	44.3	6.8	4.6	31.2
	5/24/2000	64.8	15.6	0.89	13.9
	8/16/2000	74.6	15.6	0.24	3.7
	12/18/2000	28.7	1.7	5.6	9.3
	2/6/2001	32.7	1.7	6.8	11.3
	Estimated exposure concentration (µg/m^3) =			3.63 (average)	3.81 (f = 0.02) 4.61 (f = 0.10)

Risk Assessment

Over- or under-predicting the exposure concentrations by a certain percentage may affect the conclusions of a risk assessment if the initial estimate is near the "acceptable" risk level, regardless of how that level is defined for a particular site. For example, Figures 4 and 5 show the estimated cancer risk based on a unit cancer risk factor for TCE of 2×10^{-6} (m^3/µg).[8] If the average indoor air measurements were used as the exposure concentrations, residence #18 is just above a cancer risk of 1×10^{-6}, and residence #21 is below that level. However, the consideration of residents potentially being exposed to higher concentrations of TCE in the basement might sway the decision toward a more conservative outcome. It is possible to think of cases where the argument might be the reverse. Because it is unlikely that residents would spend their entire time in the basement while at home, risk assessments based on the average basement air concentrations are inherently conservative and may result in more remediation being required than is necessary to protect human health. Conversely, assuming that residents with unfinished basements spend no time in the basement may underestimate the need for remediation. For example, substantial exposure to infiltrated contaminants might occur if the unfinished basement were remodeled into a bedroom. Concentration estimates in the basement and the rest of the house can help determine the appropriate remediation options for residences that may be affected by vapor intrusion.

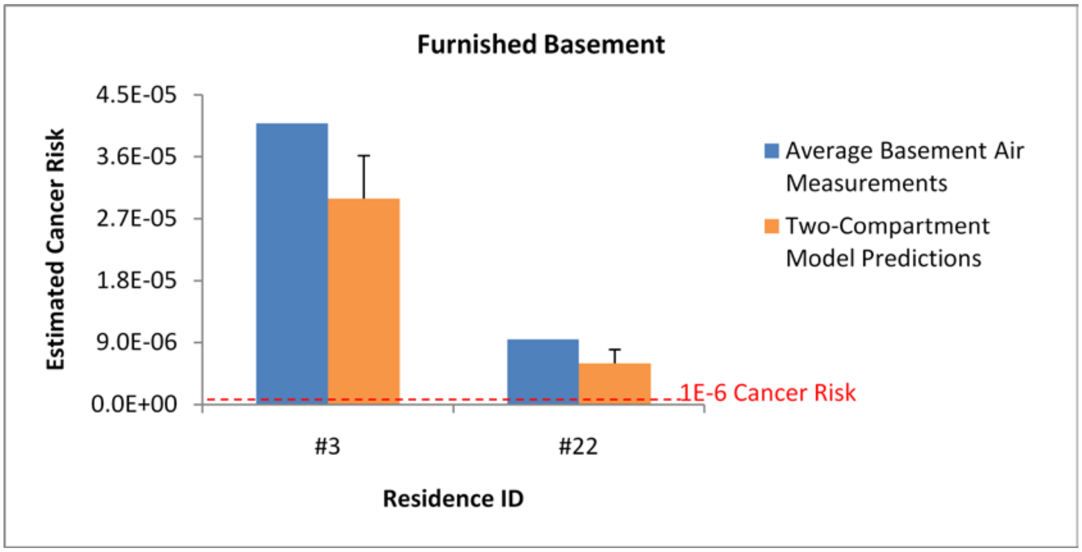

Figure 4. Predicted cancer risk based on the average basement air concentrations, and exposure concentrations calculated using a two-compartment model (see Table 5). Column height shows the median prediction. Error bar shows the 95th percentile prediction.

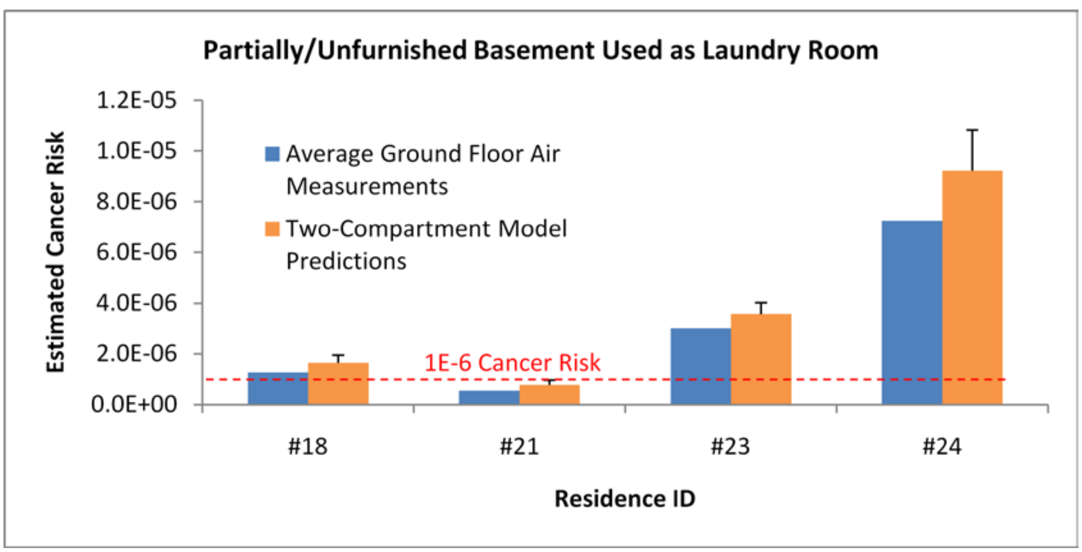

Figure 5. Predicted cancer risk based on the average indoor air concentrations, and exposure concentrations calculated using a two-compartment model (see Table 6). Column height shows the median prediction. Error bar shows the 95th percentile prediction.

SUMMARY

The TCE concentrations measured at residences near the Lowry AFB suggest higher concentrations in the basement than in the ground floor of the house. The difference in concentration between the basement and the ground floor is larger in the summer than in winter. This is likely due to a stronger stack effect driving air to migrate from the basement to the ground floor of the house in winter, and also a higher air-exchange rate in the ground floor of the house with the outdoors from opened doors and windows in summer. These observations are supported by basement air-flow studies in the literature.[3,4]

This analysis characterizes two parameters used to evaluate exposure to elevated TCE concentrations in the basement. The first parameter is the ratio between the concentrations in basement air and indoor air measured in the ground floor of the house, C_b/C_i. For reasons explained above, this ratio varies with seasons. We estimated that C_b/C_i is approximately 15.6 when the daily average outdoor temperature is warm (>60 °F), 6.8 when the temperature is moderate (40–60 °F), and 1.7 when the temperature is cool (<40 °F). These ratios were calculated using TCE concentrations measured in the basement/crawlspace air relative to indoor air from five Lowry AFB residences. The Boston multi-zonal air-flow studies also found similar ranges for C_b/C_i based on measurements from thirty-five residences with finished and unfinished basements.[4] This suggests that data from the five Lowry AFB residences are relevant data to consider, even though this subset of residences have different floor types.

The second important parameter to quantify is the fraction of time, *f*, that residents spend in the basement while at home. We used NHAPS data to calculate the median and 95th percentile values for basements that are fully finished and are likely occupied more often, and for basements that are used less frequently for laundry. The median *f* value is 0.09 for finished basements, with the 95th percentile value at 0.42. If the basement is used for laundry only, the median *f* value is 0.018, with the 95th percentile value at 0.096. The NHAPS also points out that some fraction of the population rarely goes to the basement, or is responsible for doing laundry. This evaluation shows the importance of assessing time spent in the basement when estimating potential health risks associated with vapor intrusion.

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