# New Data on Attenuation Coefficients for Crawl Spaces and Deep Soil Gas from the Lowry AFB Site, Denver, Colorado

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**Abstract**

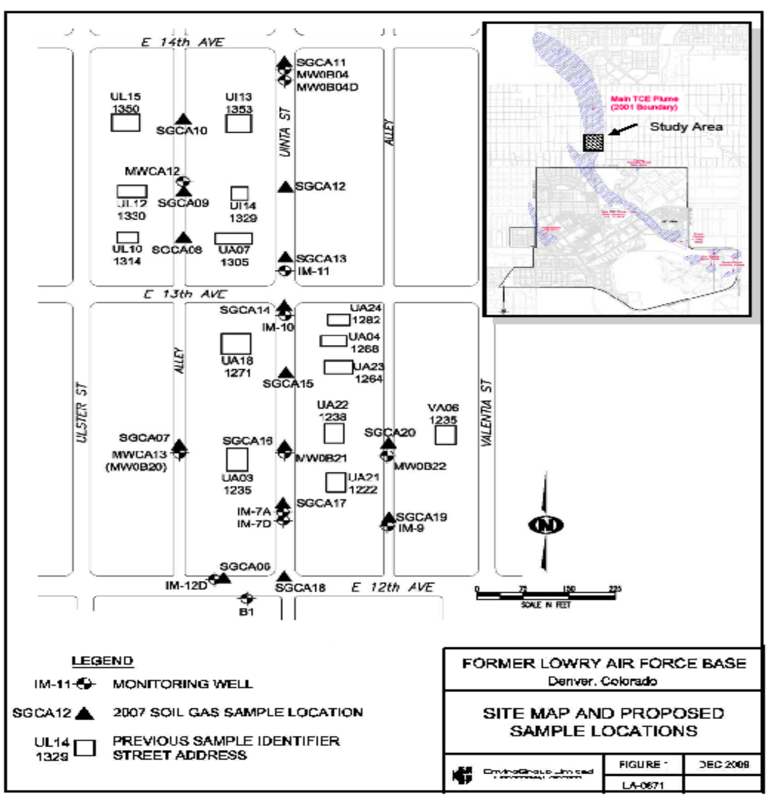
In the past few years, several rounds of paired groundwater, soil gas, sub-slab vapor, crawl space air and indoor air data have been acquired for residences over the former Lowry AFB TCE plume. These data expand on the historic data in EPA's vapor intrusion database and yield important information about the spatial and temporal variability of various types of attenuation coefficients for a site. The buildings vary greatly in construction style and age, with full basement and partial basement and partial crawl space homes. Unvented crawl space to first floor indoor air attenuation coefficients range from 0.7 to 1.0. Repeated sub-slab vapor and basement indoor air sampling, over a period of 9 years, has yielded highly consistent attenuation coefficients ($9E^{-04}$ to $1.1E^{-02}$) even though the same sub-slab point was not sampled in each event and sub-slab concentrations have decreased by nearly an order of magnitude over that time period. Deep (7 to 10 feet bgs) soil gas to indoor air attenuation coefficients are comparable to the nearby (within 75 feet) sub-slab attenuation coefficients, and adjacent deep soil gas and sub-slab vapor concentrations are generally very similar. While data from 10 shallow groundwater wells in the residential area show limited variability in TCE concentration (a range of less than a factor of 6), the soil vapor points, at basement depth, yield TCE concentrations varying over nearly two orders of magnitude. The soil gas data more closely reflects the sub-slab vapor concentrations and resultant indoor air concentrations than the groundwater data.

# INTRODUCTION

As a follow-up to three previous investigations related to indoor air, a program to sample residential indoor air, outdoor air, sub-slab vapor, soil vapor, and groundwater was implemented in January 2010 at the former Lowry Air Force Base (Lowry). The program was designed to assess whether or not observed decreases in dissolved volatile organic compound (VOC) concentrations in groundwater have resulted in comparable decreases in VOC concentrations in indoor air, sub-slab vapor, and soil vapor concentrations. The study area that was the focus of this investigation overlays the Main Trichloroethene (TCE) Plume and is bounded by 12th and 14th Avenues on the south and the north, and by Ulster and Valentia Streets on the west and east (Study Area), as shown on Figure 1.

The Colorado Department of Public Health and Environment (CDPHE) approved Work Plan described the procedures for conducting an indoor air study north of Lowry to repeat and update the 2007 indoor air study completed by Lowry Assumption, LLC (LAC) and included attempted sampling of up to 14 residences (including indoor air and sub-slab vapor) and the collection of soil vapor samples from 15 existing permanent soil vapor probes in the Study Area[1].

Figure 1. Study Area



# BACKGROUND INFORMATION

## Historical Investigation Observations

The environmental program at Lowry began in 1983 with the Air Force Installation Restoration Program. Contamination in the groundwater, primarily from TCE, was identified in three distinct plumes (i.e., Main TCE, Headquarters Area, and Fire Training Zone). The largest of the plumes, the Main TCE Plume, extends approximately three miles to the north from source areas within the former base and passes under the study area, a residential area north of the base. Compared with monitoring data from 1998-1999, average TCE concentrations in groundwater within the study area at the time of the 2010 indoor air study have dropped an average of 90%. This decrease resulted from the combination of interim remedial actions, active remediation, and natural degradation processes. The active remediation includes three full scale potassium permanganate injections that were performed in the study area in 2004, 2007, and 2009. Based on January 2010 groundwater data[2] from samples collected in the study area, there have been additional reductions in the average TCE concentration of 56.4% within the study area since the previous indoor air study was performed in 2007.

The groundwater-to-indoor air migration pathway was studied because of the potential risks from volatilization of VOCs dissolved in groundwater and their potential migration into overlying structures. During three previous investigations conducted in 1997-98 (Versar), 2001(Versar), and 2007(LAC), the groundwater-to-indoor air pathway was investigated using a combination of groundwater, indoor air, outdoor air, sub-slab vapor, and soil vapor samples[3, 4, 5]. This 2010 study focused on the same sample locations in an effort to quantify the changes in indoor air, sub-slab vapor, and soil vapor TCE concentrations (the only consistently detected VOC in groundwater), as the concentrations in groundwater have decreased substantially over time.

In December 1997, the Air Force began an investigation to delineate areas where the groundwater-to-indoor air pathway was potentially complete[3(Appendix K)]. Eight of the 16 homes sampled in 1998 by Versar[3] were tested again in one of the later studies and six of these were sampled in the present study. The 2001 Phase III groundwater-to-indoor air study[4] focused on residences overlying the center of the Main TCE Plume between 12th and 13th Street, an area which was understood to represent the worst-case scenario for transport of VOCs from groundwater-to-indoor air due to the relatively high groundwater concentrations. In that study, indoor air samples were collected in 13 residences at two month intervals over a period of one year between March 2000 and February 2001(the present study includes new sample data from four of the homes from the 2000-2001 study). Additionally, sub-slab vapor or crawlspace air, outdoor air, and groundwater samples were collected. Based on these results, the Air Force installed a mitigation system in the residence at UA03 and it began operation in March 2003, although the system was temporarily turned off during the 2007 and 2010 sampling events. These data also demonstrated that indoor air concentrations were highest in the winter samples with concentrations twice the annual average[4 (Table 5-1)].

Active remediation of the groundwater plumes with potassium permanganate began in 2004 following treatability studies and the development of the Phase II Corrective Action Plan (CAP)[6]. TCE was identified as the primary contaminant in the Lowry plumes, with subsidiary PCE. Throughout the Main TCE Plume, there have been four rounds of chemical oxidant treatment that have been completed on-base and three rounds completed off-base since the fall of 2004. For the entire period of investigation and treatment of the Main TCE plume, which began as early as 1983, there has been an average decrease in TCE concentrations in groundwater of approximately 83 to 95% for wells completed in the alluvium.

A follow-up indoor air study was implemented by LAC in 2007. Fourteen residences between $12^{th}$ and $13^{th}$ Street were targeted for indoor air and sub-slab sampling, nine of which granted access. In that study a reduction in average groundwater TCE concentrations of approximately 44% was observed, associated with reductions in the average TCE concentrations of soil vapor (30%), sub-slab air (53%), and indoor air (58%) when comparing the 2007 data to the earlier studies performed in 1998 and 2001. Essentially all sampling locations for all three media showed TCE concentration reductions compared to the previous sampling events. Further reductions in groundwater concentrations were observed in the study area following groundwater treatment in the fall of 2007.

LAC has collected groundwater data semi-annually from June 2003 through January 2010. Monitoring wells within the study area used during this program are shown on Figure 1. All of these wells have been sampled at some point during previous monitoring programs and have been analyzed for VOCs by EPA Method 8260.

Alluvial aquifer concentrations of TCE in the Study Area have declined since the earliest samples were collected in approximately 1996 and additional information is available in the OU5 Remedial Investigation[3] and the semi-annual GMP reports. In the initial groundwater-to-indoor air pathway evaluation[3 (Appendix K)] the arithmetic mean alluvial TCE concentration, based on data reported for three wells in 1996-1998 in the Study Area and the area immediately south (Heritage Estates), was 110 micrograms per liter (μg/L). The average concentration in 10 wells from the 2007 study was 25 μg/L, and the current average concentration for the same 10 wells in January 2010 was 10.9 ug/L.

The EPA Vapor Intrusion Database includes data from 13 homes sampled during the Versar 2000-2001 study. Five of these homes had crawl spaces sampled. Unfortunately, at that time, no soil gas samples were collected contemporaneous with the indoor air and sub slab sampling. In addition, at that time, only one alluvial groundwater well was sampled.

The current study allows a more detailed comparison of attenuation factors between media for one of the early datasets incorporated in the EPA Vapor Intrusion Database that was, and still is, one of the critical datasets cited for crawl space to indoor air attenuation. In addition, the 12 year history of paired deep soil gas sampling in conjunction with sub-slab, groundwater and indoor sampling allows an evaluation of both the spatial and temporal variability of multi-media attenuation factors in a well studied area.

# INVESTIGATION PROCEDURES

This section presents procedures for contacting and interviewing candidate residences, sampling procedures and collection methods for indoor air, sub-slab vapor, soil vapor, outdoor air, and groundwater samples. All work was performed in accordance with a project Quality Assurance/Quality Control (QA/QC) Plan.

## Residential Sampling Locations

The residential sampling program was based upon the attempted sampling of 14 previously sampled buildings in the Study Area to assess changes in VOC concentrations in indoor air and sub-slab vapor [3,4,5]. During the previous studies, indoor air and sub-slab vapor samples were collected in a total of 14 residences overlying the Main TCE Plume with full or partial basements. During the March 2007 study, attempts were made to resample all 14 homes; however, permission to sample was received for only nine of these residences[5]. During the January 2010 study, although attempts were again made to sample all 14 homes, permission to sample was received from only nine of these residences, six of which had been sampled in 2007. Two of the homes did not permit sampling during either the 2007 study or the present study. These two homes are omitted from tabulations and further discussion so that only 12 homes appear in the historical indoor air comparison table.

### *Candidate Interview Documentation*

Prior to sampling activities, a resident at each sampling location was interviewed by EnviroGroup personnel. An approved questionnaire was administered during sampling activities. A home inspection and floor plan sketch to establish construction details relevant to vapor intrusion evaluation (such as locations of dry wells, sumps, foundation cracks, type of heating and ventilation system, sources of outdoor air, etc.) and a chemical inventory were completed to identify obvious sources or activities that could produce COCs and potentially affect indoor air samples.

The radon mitigation system at UA03 was turned off approximately one week prior to indoor air sampling.

## Indoor and Outdoor Air Sampling Procedures

Two indoor air samples and one sub-slab vapor sample were collected from each of the nine previously sampled buildings. Indoor air samples were collected from the basement and first floor. Unvented crawl space samples were collected from three of the homes with partial basements. For quality control/quality assurance (QA/QC) purposes, a contemporaneous outdoor air sample was intended to be collected during each day of indoor air and sub-slab vapor sample collection. Samples were not collected during two days of indoor air sampling due to an insufficient number of sample canisters. The five outdoor air samples collected are considered to be adequately representative for the two locations sampled on these dates.

Indoor air sample locations were selected away from vents, windows, and chemical sources, in a centrally-located area, at a height of approximately three feet above the floor to represent the breathing zone. Residents were asked to keep windows and doors closed during the entire sampling period.  The outdoor air samples were collected immediately outside the buildings (i.e., not closer than five feet), on the upwind side, away from any exhaust from the buildings (e.g., exhaust vents) or wind obstructions, at a height of approximately three feet above ground level, and distant from any obvious source of VOCs at the residences.

Indoor and outdoor air samples were collected over a 24 hour time period utilizing dedicated, laboratory-set regulators and 6 Liter (L) Summa® (or equivalent) canisters supplied and individually certified clean to SIM reporting limit levels by Air Toxics Ltd., of Folsom, California (Air Toxics).  Each canister had an initial field vacuum reading of at least 24 inches of mercury (Hg) prior to sampling and had a final field vacuum reading of 3 inches Hg or greater upon the completion of sample collection.

Historical and current indoor air sample locations are shown on Figure 1.

## Sub-slab Vapor Sampling Procedures

After the indoor air samples were collected, one sub-slab vapor sample was collected from each of the nine residences.  Sub-slab vapor samples were collected near the same locations where the previous samples were collected when possible (previous locations were found in approximately half of the sampled homes).

When possible, and as permitted by the owners, the sub-slab vapor samples in residences were collected in a central location, away from foundation footings and obvious slab perforations. Temporary probes were installed by drilling approximately 1/2 or 3/4 inch outer diameter (OD) holes through the basement or ground floor slabs, as applicable, and no further than 2 inches into the underlying sub-slab materials.  The 1/2 or 3/4 inch OD hole was then over-drilled with a larger 1.5 inch OD hole to a depth of about 1 inch below the slab surface.  A new, clean length of 0.190 inch inner diameter (ID) x 0.25 inch OD Nylaflow® tubing, fitted with an acrylic screen, was inserted into the hole to the base of slab and sealed in the hole with hydrated bentonite.

Sub-slab vapor samples were collected using current state of the art procedures.  During sub-slab vapor sampling activities, a clean, small plastic or stainless steel shroud with two small ports was placed over each sub-slab vapor probe and weighted down.  An air-tight seal of foam was placed on the ground surface around the edge of the shroud where it contacted the ground.  The sub-slab vapor probe tube, which was fitted with an air-tight valve, was then extended up through the air-tight seal of foam to the exterior side of the shroud.

Each sub-slab vapor tube, connected to an air-tight valve, was then connected with a Tedlar bag attached to one side of the valve and the sampling tube on the other side of the valve (both outside of the shroud).  Prior to purging or sampling activities, helium tracer gas was released via a small diameter tube through a port in the shroud into the enclosure beneath the shroud.  A sample of the air inside the shroud was measured through the second port using a portable helium detector to determine the concentration of helium within the enclosure beneath the shroud.

As historically done, sub-slab vapor probes were purged (i.e., up to 0.5 L) at a flow rate of 100 to 200 milliliters (mL) per minute, through the shroud into a 60 mL calibrated gas-tight syringe and transferred to the Tedlar bag. The Tedlar bag was then connected to a portable helium detector to measure for the presence of helium gas in the purged vapor. If high concentrations (>10% of the shroud concentration) of helium were observed in the purge vapor, the sub-slab probe seal was checked and/or enhanced to reduce the infiltration of ambient air into the enclosure and another sample collected. If helium concentrations were less than 10%, a sub-slab vapor sample was collected for analysis. Upon completion of sampling activities, all sub-slab vapor probes were removed and holes filled with bentonite and sealed with concrete.

Sub-slab vapor samples were collected over approximately a 10 minute time period utilizing dedicated, laboratory-set regulators and 1 L Summa® (or equivalent) canisters supplied and individually certified clean to TO-15 SCAN reporting limit levels by Air Toxics. Each canister had an initial field vacuum reading of at least 24 inches Hg prior to sampling and had a final field vacuum reading of 4 inches Hg or greater upon the completion of sample collection.

Historical and current sub-slab vapor sample locations are shown on Figure 1.

## Soil Vapor Probe Installation and Sampling Procedures

Using direct push methods, a continuous core was collected to a depth of ten feet below ground surface to identify a permeable zone for sampling at a depth representative of the bottom of a basement slab. After the soil vapor sampling location was cored, a small OD Nylaflow® sampling tube (i.e., 1/4 inch) with a stainless steel vapor sampling probe tip was installed at each location to a depth of seven to ten feet below ground surface, with most in the nine to ten foot depth range. The probe tip was placed in the middle of approximately one foot of silica sand pack. One foot of granular bentonite was placed above the sand pack, followed by hydrated bentonite to within approximately one foot of ground surface. Silica sand was then placed above the hydrated bentonite to the surface. A gas-tight fitting was installed at the top of the sampling tube and a flush-mount surface completion installed.

Soil vapor samples were collected using helium shrouds, following the same method as for the sub-slab installations. In the case of soil vapor points, as was historically done for these points, 1.0 L was purged at a flow rate of 100 to 200 mL per minute, through the shroud into a 60 ml calibrated gas-tight syringe and transferred to the Tedlar bag for helium detection.

Soil vapor samples were collected over approximately a 10 minute time period utilizing dedicated, laboratory-set regulators and 1 L Summa® (or equivalent) canisters supplied and individually certified clean to TO-15 SCAN reporting limit levels by Air Toxics. Each canister had an initial field vacuum reading of at least 23 inches Hg prior to sampling and had a final field vacuum reading of 3 inches Hg or greater upon the completion of sample collection.

Soil vapor sample locations are shown on Figure 1.

## Groundwater Sample Collection Procedures

Groundwater samples from 10 alluvial monitoring wells were collected to assess the current concentrations of COCs. The alluvial wells are screened across the water table, typically with 10 foot screened intervals. Two wells (MWCM15 and MWOB21) have five foot screen intervals due to a very thin (3.5 ft) saturated zone for these wells.

Groundwater sampling was conducted using low-flow techniques and dedicated pumps. Wherever feasible, the techniques followed were consistent with historical monitoring procedures. Monitoring wells utilized dedicated bladder pumps with dedicated tubing to prevent any cross contamination.

The low-flow sampling techniques do not require purging three (3) to five (5) times the volume of water in the well as is required for traditional techniques to eliminate the stagnant water standing in the well prior to sample collection. Low-flow purging and sampling mobilizes only the water in the immediate area of the pump intake. Monitoring key water quality parameters for stability was utilized to determine when fresh aquifer water was being removed. The water quality parameters monitored, and the amount of variance of each parameter which established stability, were: temperature, ±0.2 degrees Celsius (ºC); pH, ±0.2 units; conductivity, ±2.0 percent of reading; and DO, ±0.2 milligrams per liter (mg/L). The rate of purging was maintained below 1.0 liters per minute, and drawdown in the well was held to less than 25 percent of the saturated thickness[7].

Groundwater samples were analyzed for VOCs by EPA Method 8260B. Monitoring well locations are shown on Figure 1.

## Laboratory Procedures

### Indoor Air, Outdoor Air, Sub-Slab Vapor, and Soil Vapor Samples

All samples (indoor air, outdoor air, sub-slab vapor, and soil vapor) were analyzed using a modified Method TO-15[8], for 10 VOCs by Air Toxics, Inc. using internal standard operating procedures (SOPs). Indoor and outdoor air samples were analyzed in SIM mode with TCE reporting limits ranging from 0.025 to 0.037 ug/m$^3$. Soil vapor and sub-slab samples were analyzed in SCAN mode with TCE reporting limits ranging from 6 to 8 ug/m$^3$.

For TCE, all results have been reported down to the method detection limit (MDL) with a "J" qualifier added for values between the RL and MDL to indicate an estimated value.

### Quality Assurance/Quality Control

The quality assurance objective for field and laboratory investigations is to provide defensible analytical data that are accurate, precise, representative, comparable between labs and complete to the degree defined by the project QA/QC Plan.

### Laboratory QA/QC

Laboratory QA/QC analytical results were reviewed during data validation. Results indicated acceptable accuracy (within 30%) and precision (within 15%) in the analyses.

The two laboratory duplicates for soil vapor yielded excellent agreement for TCE with Relative Percent Differences (RPDs) of less than 14%. The two laboratory duplicates for sub-slab vapor yielded excellent agreement for TCE with RPDs of less than 4%. Laboratory duplicates for indoor air yielded excellent agreement for TCE with RPDs of less than 5%.

**Field QA/QC**

Field QA/QC samples (i.e. duplicates and outdoor air samples) and canister vacuums were reviewed to assure compliance with the project QA/QC plan.

***Field Duplicates***

Indoor air field duplicates consisted of two canister samples collected simultaneously and side by side. In the case of soil vapor and sub-slab vapor samples, simultaneous Summa canister samples were collected through a "T" fitting. Two indoor air, four sub-slab vapor, two soil vapor, and one groundwater field duplicate samples were collected during the 2010 investigation.

The two field duplicates for soil vapor yielded acceptable agreement for TCE with Relative Percent Differences (RPDs) of 40 to 50%.

The four field duplicates for sub-slab vapor yielded excellent agreement for TCE with RPDs of less than 15%. The two field duplicates for indoor air yielded excellent agreement for TCE with RPDs of less than 16%. The field duplicates for groundwater yielded identical results for TCE.

***Canister Vacuums***

A Dwyer DPGA-00 digital vacuum gauge was used for all Summa canister vacuum measurements in the field. Initial field vacuums should be greater than 24 inches Hg in Denver for canisters received from labs at sea level. One soil gas sample (EGSGCA14) had an initial field vacuum of -23 inches Hg possibly indicating minor canister leakage during shipment to the field. Insufficient spare canisters were available, so this canister was used for sampling. This sample may have a slight low bias. Two soil gas samples had substantially lower (5 to 7 inches Hg) laboratory vacuums compared to final field vacuums (SGCA11 and SGCA16) indicating that the canisters might have leaked during shipment back to the laboratory. Given the relatively high TCE concentrations in these soil vapor samples, such leakage may have resulted in a low bias in the results. Two indoor air samples (LAI08 and LAI17) had low laboratory vacuums (3 to 4 inches Hg) compared to final field vacuums, indicating that the canisters might have leaked during shipment back to the laboratory. Although sample LAI17 agrees fairly well with the field duplicate at this location, the higher TCE concentration from the duplicate was used for comparison purposes. Sample LAI08 from the basement of UA22 may be biased somewhat low due to potential canister leakage during shipment. The higher TCE concentration from the first floor sample was utilized for comparison purposes at this home.

INVESTIGATION RESULTS

## Indoor Air Investigation

### *Indoor Air and Sub-slab Analytical Results*

The results from indoor air and sub-slab samples collected by EnviroGroup from nine homes in January 2010 are shown on Figure 2 and Table 1. TCE concentrations ranged from 0.053 to 1.7 µg/m$^3$ in indoor air and ranged from less than 1.17 to 260 µg/m$^3$ in sub-slab vapor.

Table 1. Indoor and outdoor Air TCE Results, January 2010 (µg/m$^3$)

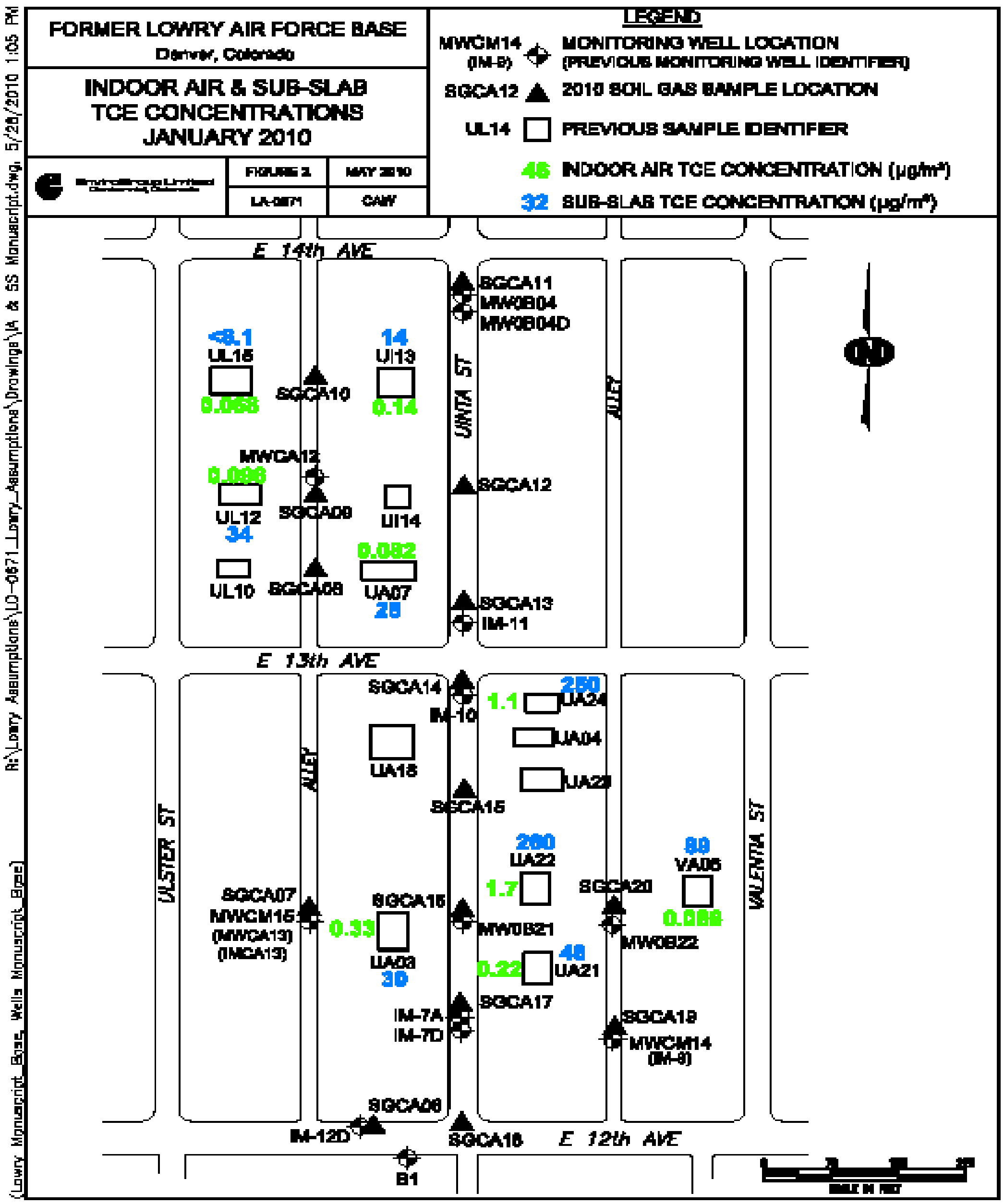
| Residence | Basement TCE | Crawl Space TCE | First Floor TCE | Outdoor Air TCE |
|---|---|---|---|---|
| UA21 | 0.22 | | 0.15 | 0.046 |
| UA03 | 0.33 | | 0.22 | 0.089 |
| VA06 | 0.081 | | 0.086 | |
| UA22 | 1.6 | | 1.7 | 0.056 |
| UA24 | 0.89 | 1.2 | 1.1 | 0.038 |
| UA07 | 0.064 | | 0.082 | 0.029 J |
| UL12 | 0.096 | 0.089 | 0.063 | |
| UL15 | 0.068 | | 0.053 | |
| UI13 | 0.14 | 0.094 | 0.096 | |

The arithmetic average TCE concentration in the 9 basement indoor air samples was 0.395 µg/m$^3$ and the median was 0.14 µg/m$^3$, with a range of 0.064 to 1.6 µg/m$^3$.

The arithmetic average TCE concentration in the nine first floor indoor air samples was 0.394 µg/m$^3$ and the median was 0.096 µg/m$^3$, with a range of 0.053 to 1.7 µg/m$^3$. As shown in Table 1, the first floor indoor air results were very similar to those in the basement (within plus or minus 35%), or crawl space when present, suggesting the lack of notable indoor air sources of TCE on the first floor of these homes.

The arithmetic average TCE concentration in the three crawl space indoor air samples was 0.46 µg/m$^3$ with a range of 0.089 to 1.2 µg/m$^3$. For the three locations with crawl space data the first floor TCE results were very comparable to the crawl space results, with apparent attenuation factors of 0.7 to 1.0 between the crawl space and first floor, suggesting minimal attenuation from crawl space to indoor air.

Figure 2:  Indoor Air and Sub-slab TCE Results (January 2010).




### *Outdoor Air Analytical Results*

The TCE concentrations from outdoor air samples collected from the vicinity of five homes in January 2010 ranged from 0.029 to 0.089 µg/m$^3$, with an average of 0.052 µg/m$^3$.

### *Sub-Slab Vapor Analytical Results*

The results from sub-slab vapor samples collected from nine homes in January 2010 are shown on Figure 2 and in Table 2. TCE concentrations ranged from below detection (< 1.1 µg/m$^3$) to 260 µg/m$^3$. The arithmetic average TCE concentration in these 9 sub-slab vapor samples was 84 µg/m$^3$ using the detection limit as the concentration for the one sample with non-detectable results, and the median was 41 µg/m$^3$.

**Table 2**. Sub-slab Vapor to Indoor Air TCE Attenuation Factors.

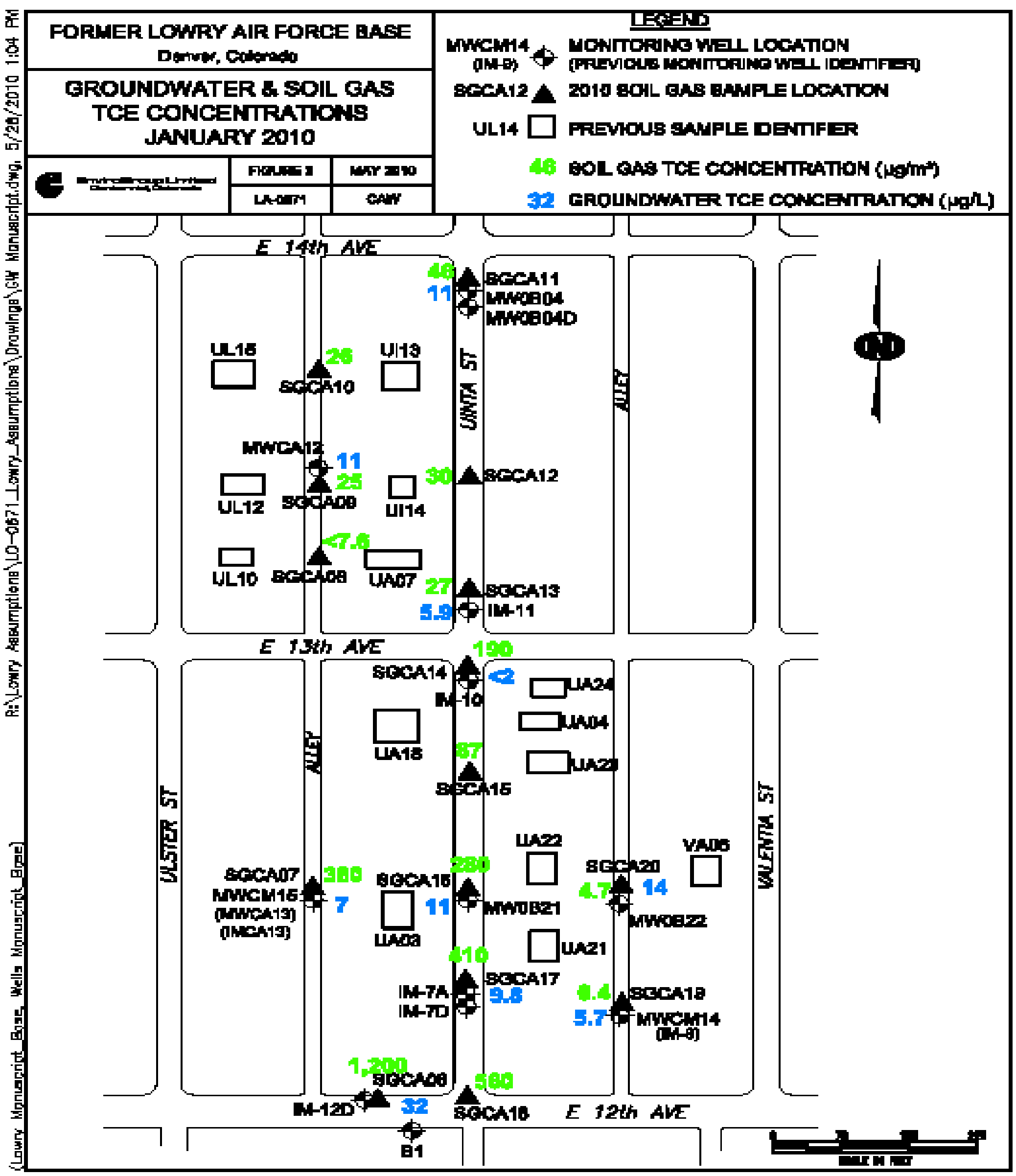
| Sample Location | Basement Indoor Air TCE Concentration (ug/m$^3$) | | | | Sub-Slab TCE Concentration (ug/m$^3$) | | | | 2010 SS/IA AF | 2007 SS/IA AF | 2001 SS/IA AF | 1998 SS/IA AF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2007 | 2001 | 1998 | 2010 | 2007 | 2001 | 1998 | | | | |
| UA21 | 0.22 | 0.35 | 0.58 | - | 48 | 160 | 111 | - | 4.6E-03 | 2.2E-03 | 5.2E-03 | |
| UA03 | 0.33 | 9.7 | 43 | 0.9# | 30 | 1100 | 3,145 | 12,016 | 1.1E-02 | 8.8E-03 | 1.4E-02 | 7.5E-05# |
| VA06 | 0.086 | - | - | 0.26 | 89 | - | - | 1.62 | 9.7E-04 | | | |
| UA22 | 1.7 | 5.6 | 6.6 | - | 260 | 480 | 808 | - | 6.5E-03 | 1.2E-02 | 8.2E-03 | |
| UA18 | - | 0.98 | 0.81 | - | - | 940 | 119 | - | | 1.0E-03 | 6.8E-03 | |
| UA24 | 1.1 | 5.1 | 5.7 | - | 250 | 1400 | 2,380 | - | 4.4E-03 | 3.6E-03 | 2.4E-03 | |
| UA07 | 0.082 | 0.11 | - | 1.6 | 28 | - | - | 1340 | 2.9E-03 | | | 1.2E-03 |
| UL10***** | - | 0.53* | - | 0.34 | | <0.98 | - | 201 | | NA | | 1.7E-03 |
| UI14 | - | 0.67 | - | 0.23# | - | 200 | - | 502 | | 3.4E-03 | | 4.6E-04# |
| UL12 | 0.096 | - | - | 0.27 | 34 | - | - | 79 | 2.8E-03 | | | 3.4E-03 |
| UL15 | 0.068 | 0.16 | - | 0.7 | <1.17 | 14 | - | <1.03 | NA | 1.1E-02 | | |
| UI13 | 0.14 | - | - | 0.38 | 14 | - | - | 208 | 1.0E-02 | | | 1.8E-03 |
| Average | | | | | | | | | 5.4E-03 | 6.0E-03 | 7.3E-03 | 2.0E-03 |
| Median | | | | | | | | | 4.5E-03 | 3.6E-03 | 6.8E-03 | 1.4E-03 |

Note: Blank cell indicates sample was not analyzed in that sampling event
*Subslab system operating in 2007
# anomalous result suspected of low bias due to open house conditions

## Soil Vapor Investigation

The results from soil vapor samples collected from 15 permanent, deep (eight to ten foot) soil vapor points in January 2010 are shown on Figure 3. TCE concentrations ranged from below detection (< 7.6 µg/m$^3$) to 1200 µg/m$^3$. The arithmetic average TCE concentration in these 15 soil vapor samples was 218 µg/m$^3$ using the detection limit as the concentration for the one sample with non-detectable results.

Figure 3: Groundwater and Soil Vapor TCE Results (January 2010).



## Groundwater Investigation

The results from groundwater samples collected in January 2010 are presented in Figure 3. TCE concentrations ranged from below detection (< 2 µg/L) to 32 µg/L in alluvial groundwater. The arithmetic average TCE concentration in the ten alluvial wells was 10.9 µg/L using the detection limit as the concentration for the one sample with non-detectable results. Tetrachloroethene was not detected in any of the alluvial aquifer samples.

## Groundwater-to-Indoor Air Pathway Evaluation

***Indoor vs Outdoor Air Concentrations***

The indoor air TCE results for UL12 (0.063 to 0.089), UA07 (0.064 to 0.082), VA06 (0.081 to 0.086), and UL15 (0.053 to 0.068) are only marginally higher than the outdoor air TCE concentrations (arithmetic average of 0.052 µg/m$^3$), suggesting a dominant outdoor source for TCE in these four homes. The remaining five homes have indoor air TCE results greater than the outdoor air, at least in basement samples.

For TCE, the first floor indoor air results are comparable to those in the basement, or crawl space when present, suggesting the lack of notable indoor air sources of TCE on the first floor of these homes.

***Comparison of Indoor Air to Sub-slab Vapor Concentrations***

The sub-slab TCE concentration was not detectable at UL15, suggesting that the measured indoor air TCE at this home is attributable to background sources (probably largely outdoor air in this case). The apparent sub-slab to indoor air attenuation for the 2010 result at UI13 is significantly less than that for the historical data when sub-slab concentrations were higher. This suggests that a substantial portion of the measured indoor air TCE at this home is due to outdoor air and indoor sources.

***Comparison of Indoor Air to Soil Vapor Concentrations***

The indoor air results for UA21 are somewhat low compared to the soil vapor points to the west of the home, but they may reflect the very low soil vapor TCE concentrations to the east of this home (see Figure 3). Likewise, the indoor air TCE results at UA03 are low compared to other locations with similar nearby soil vapor TCE concentrations. In this case, it is probable that the sub-slab depressurization system had not been off for a long enough time period (e.g., more than one week) to allow the indoor air and sub-slab vapor concentrations to re-equilibrate.

***Comparison of Sub-slab Vapor to Soil Vapor Concentrations***

The sub-slab TCE results for UA03 are low compared to that nearby soil vapor and compared to historical sub-slab results. The sub-slab TCE may not have sufficiently rebounded in the one week after the radon system was turned off and the samples were collected. The indoor air TCE results for this home are also low, suggesting that insufficient time was allowed for the sub-slab and indoor air at this home to re-equilibrate after the radon system was turned off. The remaining homes have sub-slab TCE concentrations comparable to those in adjacent soil vapor.

### *Comparison of Indoor Air to Groundwater Concentrations*

Alluvial groundwater TCE concentrations show little variation within the vicinity of the residences studied (<2 to 14 µg/L), with most in the range of 6 to 12 µg/L (Figure 3). No clear spatial relationship is apparent between January 2010 groundwater concentrations and concurrent indoor air concentrations, other than generally higher indoor air concentrations along the center line of the groundwater plume.

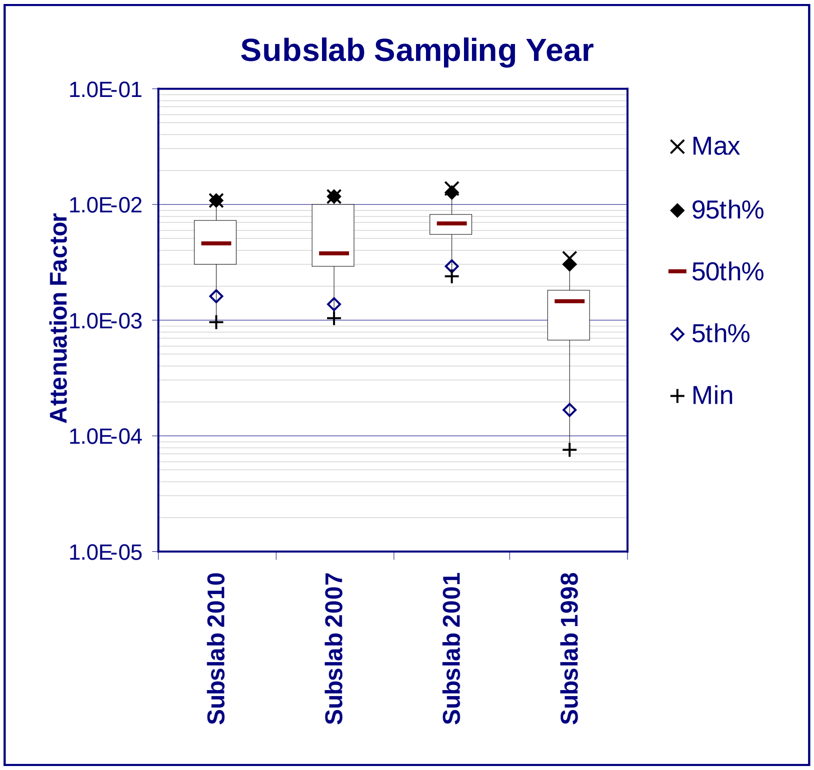
## Attenuation Factors

The reduction in vapor phase concentration from one media to another is called attenuation. When expressed as a ratio of the concentration in one media (indoor air) compared to another, this is termed an "attenuation factor". Attenuation factors for sub-slab vapor to indoor air, soil vapor to indoor air, groundwater to soil vapor, and groundwater-derived vapor to indoor air are calculated for current and historical data as part of the vapor intrusion pathway evaluation. The evaluation of attenuation factors provides context for the data by allowing comparisons across the study area and to data at other sites around the country. It also provides an understanding of how the site specific data compare to standard default assumptions for the groundwater-to-indoor air pathway, such as those incorporated into those utilized by EPA and CDPHE Vapor Intrusion Guidances for groundwater to indoor air, soil vapor to indoor air, and sub-slab vapor to indoor air attenuation factors [9, 10, 11].

### *Attenuation from Sub-slab Vapor to Indoor Air*

Attenuation factors for TCE in sub-slab vapor compared to indoor air from the January 2010 sampling event range from $9 \times 10^{-4}$ to $1.1 \times 10^{-2}$, with an arithmetic mean of $5.4 \times 10^{-3}$ and median of $4.5 \times 10^{-3}$ (Table 2). These ranges are very similar to those determined from previous results at these homes, and are nearly identical for individual homes (within a factor of two) as shown in Table 2 and Figure 4, with the exception of the 1998 results for UA03 and UI14. These two 1998 apparent attenuation factors are anomalously small compared to subsequent sampling events at these two homes and are considered to be non-representative. In the case of UA03, the 1998 indoor air TCE concentration was more than an order of magnitude lower than the 2001 indoor air concentration, although the sub-slab concentrations were comparable in the two events. This finding of anomalously low indoor air concentrations is consistent with the summer season open house sampling conditions (all windows open) documented for these two homes in the 1998 sampling event[3(Table 6-14)] compared to the other homes sampled in 1998. Note that the sub-slab attenuation factors are substantially smaller than the default sub-slab to indoor air attenuation factor of 0.1 used in the 2002 EPA Vapor Intrusion Guidance[9], but are comparable to the median sub-slab to indoor air attenuation factor of $4.7 \times 10^{-3}$ for background screened data in the 2010 EPA VI database[11].

Figure 4. Sub-slab TCE Attenuation Factors versus Sampling Year




***Attenuation from Soil Vapor to Indoor Air***

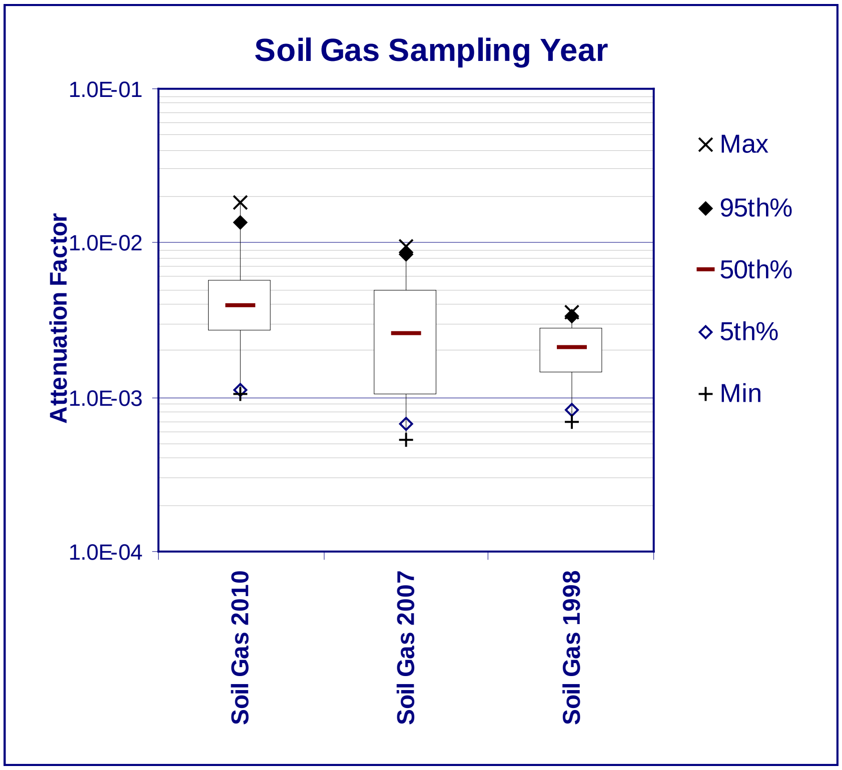
Attenuation factors for TCE in soil vapor points nearest the nine homes compared to indoor air from the January 2010 sampling event range from 1.1x $10^{-3}$ to 1.8 x $10^{-2}$ (Table 3), similar to the sub-slab to indoor air attenuation factors. These ranges are very similar to those determined from previous results, and are nearly identical for individual homes (within a factor of two) as shown in Table 3 and Figure 5. The median soil vapor to indoor air attenuation factor for the 2010 data is 3.8 x $10^{-3}$, very similar to (within 17%) the median sub-slab to indoor air attenuation factor for these nine homes. It should be noted that the indoor air TCE results at the home with the lowest apparent attenuation (VA06) are only slightly greater than the outdoor air TCE and are well within the range of typical indoor air background in Denver[12]. No measurable vapor intrusion related TCE appears to be present in the indoor air at this home.

**Table 3**. Soil Gas to Indoor Air TCE Attenuation Factors.

| Sample Location | Indoor Air TCE Concentration ($ug/m^3$) 2010 | 2007 | 1998 | Closest Soil Gas Point | Soil Gas TCE 2010 $ug/m^3$ | Soil Gas TCE 2007 $ug/m^3$ | Soil Gas TCE 1998 $ug/m^3$ | 2010 SG/IA AF | 2007 SG/IA AF | 1998 SG/IA AF |
|---|---|---|---|---|---|---|---|---|---|---|
| UA21 | 0.22 | 0.35 | - | SGCA17&19 | 208 | 653 | 1393 | 1.1E-03 | 5.4E-04 | |
| UA03 | 0.33 | 9.7 | 0.9# | SGCA16 | 280 | 1500 | 4391 | 1.2E-03 | 6.5E-03 | NA |
| VA06 | 0.086 | - | 0.26 | SGCA20 | 4.7 | 7.6 | 74 | <1.8E-02 | | 3.5E-03 |
| UA22 | 1.7 | 5.6 | - | SGCA16 | 280 | 1500 | 4391 | 6.1E-03 | 3.7E-03 | |
| UA18 | - | 0.98 | - | SGCA15 | 87 | 220 | | | 4.5E-03 | |
| UA24 | 1.1 | 5.1 | - | SGCA14 | 190 | 530 | 15# | 5.8E-03 | 9.6E-03 | |
| UA07 | 0.082 | 0.11 | 1.6 | SGCA13 | 27 | 120 | | 3.0E-03 | 9.2E-04 | |
| UI14 | - | 0.67 | 0.23# | SGCA12 | 30 | 470 | 1895 | | 1.4E-03 | NA |
| UL12 | 0.096 | - | 0.27 | SGCA09 | 25 | 110 | 388 | 3.8E-03 | | 7.0E-04 |
| UL15 | 0.068 | 0.16 | 0.7 | SGCA10 | 26 | 150 | | 2.6E-03 | 1.1E-03 | |
| UI13 | 0.14 | - | 0.38 | SGCA10 | 26 | 150 | | 5.4E-03 | | |
| Average | 0.42 | 2.83 | 0.64 | | 108 | 492 | 2089 | 3.6E-03 | 3.5E-03 | 2.1E-03 |
| Median | 0.14 | 0.83 | 0.38 | | 30 | 220 | 1644 | 3.8E-03 | 2.6E-03 | 2.1E-03 |

Note: Blank cell indicates sample was not analyzed in that sampling event
# Anomalously low value suspected of low bias. Excluded from attenuation factors
**VA06 indoor air result from 2010 is considered to be dominated by background outdoor air and excluded from average attenuation factor**

Figure 5. Soil Vapor to Indoor Air TCE Attenuation Factors




***Attenuation from Groundwater to Soil Vapor***

Groundwater derived vapor concentrations at equilibrium are determined by multiplying the groundwater concentration by the Henry's Law Constant for a compound (adjusted for the groundwater temperature) and converting units to $\mu g/m^3$ from µg/L. These calculated equilibrium soil gas concentrations (at the water table) were assumed to be comparable to the measured soil gas concentrations at approximately eight to ten foot depth. The ratio of measured soil gas TCE to the calculated groundwater-derived soil gas is the groundwater to soil gas attenuation factor. For the January 2010 sampling event these ranged from $1.5 \times 10^{-3}$ to $2.5 \times 10^{-1}$, and average $8.3 \times 10^{-2}$ (not shown). Similar results were found for the 2007 paired groundwater and soil gas sampling event.

The measured soil gas TCE concentrations are about 10% of what would be predicted just above the water table for equilibrium partitioning according to Henry's Law, probably due to mass transfer limitations across the saturated zone. Many sites report similar findings of approximately 10% of the expected equilibrium soil gas concentration for deep soil gas samples[13].

***Attenuation from Groundwater to Indoor Air***

Attenuation factors for TCE in groundwater compared to indoor air from the January 2010 sampling event range from $2.6 \times 10^{-5}$ to $8.4 \times 10^{-4}$, with an arithmetic average of $2 \times 10^{-4}$ and median of $6.3 \times 10^{-5}$ (Table 4). These ranges are very similar to those determined from previous groundwater and indoor air sampling events (Table 4). The 2010 median groundwater to indoor air attenuation factor is essentially equivalent to the median attenuation factor for the coarse soil types ($8.4 \times 10^{-5}$) in the EPA VI Database[11].

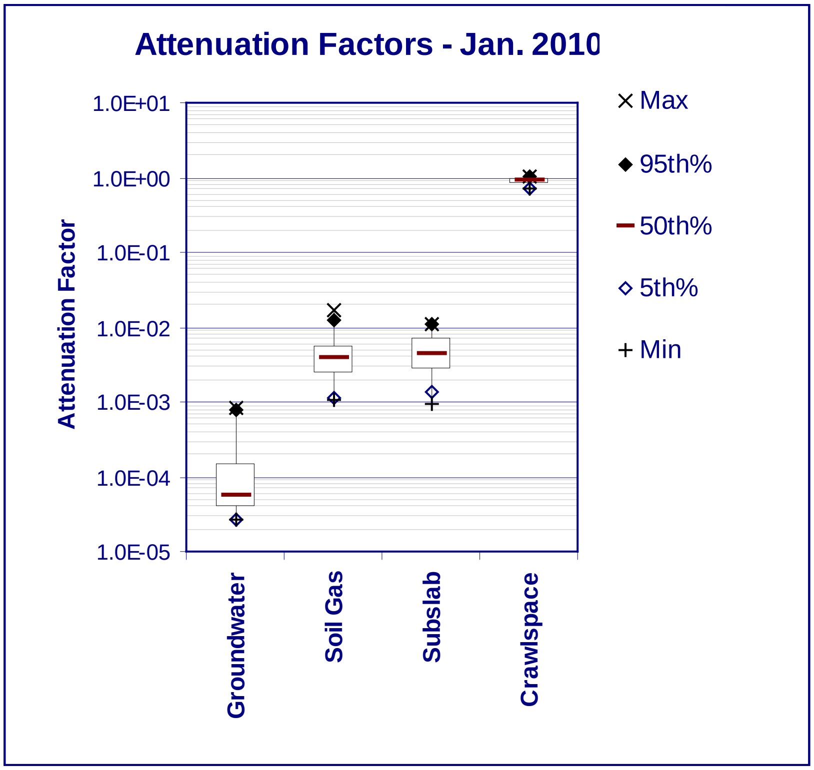
A statistical summary of the attenuation factors between the various media is shown in Figure 6. Note the excellent agreement between the sub-slab and deep soil vapor attenuation factors.

**Table 4.** Groundwater to Indoor Air TCE Attenuation Factors

| **Sample Location** | **Indoor Air TCE Concentration (ug/m$^3$)** | | | | Closest GW well | GW 2010 | GW 2007 | GW 2001 | GW 1998 | 2010 GW/IA AF | 2007 GW/IA AF | 2001 GW/IA AF | 1998 GW/IA AF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **2010** | **2007** | **2001** | **1998** | | ug/L | ug/L | ug/L | ug/L | | | | |
| UA21 | 0.22 | 0.35 | 0.58 | - | IM-7A | 9.8 | 31 | | | 1.0E-04 | 5.1E-05 | | |
| UA03 | 0.33 | 9.7 | 43 | 0.9# | IM-7A | 9.8 | 31 | | | 1.5E-04 | 1.4E-03 | | |
| VA06 | 0.086 | - | - | 0.26 | MWOB22 | 14 | 8.1 | | 15 | 2.8E-05 | | | 7.8E-05 |
| UA22 | 1.7 | 5.6 | 6.6 | - | MWOB21 | 11 | 46 | 140 | 140 | 7.0E-04 | 5.5E-04 | 2.1E-04 | |
| UA18 | - | 0.98 | 0.81 | - | IM-10 | | 26 | | | | 1.7E-04 | | |
| UA24 | 1.1 | 5.1 | 5.7 | - | IM-11 | 5.9 | 23 | | | 8.4E-04 | 1.0E-03 | | |
| UA07 | 0.082 | 0.11 | - | 1.6 | IM-11 | 5.9 | 23 | | | 6.3E-05 | 2.2E-05 | | |
| UL12 | 0.096 | - | - | 0.27 | MWCA12 | 11 | 21 | | | 3.9E-05 | | | |
| UL15 | 0.068 | 0.16 | - | 0.7 | MWCA12 | 11 | 21 | | | 2.8E-05 | 3.4E-05 | | |
| UI13 | 0.14 | - | - | 0.38 | MWOB04 | 11 | 41 | | 110 | 5.7E-05 | | | 1.6E-05 |
| Average | | | | | | 10 | 27 | 140 | 88 | 2.2E-04 | 4.6E-04 | 2.1E-04 | 4.7E-05 |
| Median | | | | | | 11 | 25 | 140 | 110 | 6.3E-05 | 1.7E-04 | 2.1E-04 | 4.7E-05 |

# Anomalously low value suspected of low bias (note that 2000 to 2001 indoor air TCE ranged from 1.4 to 51 ug/m$^3$ at this home)

Figure 6.  TCE Attenuation Factors for Residences in January 2010.




| | Attenuation Factor Type (Jan. 2010 Data) | | | |
|---|---|---|---|---|
| Statistic | Groundwater | Soil Gas | Subslab | Crawlspace |
| Min | 2.6E-05 | 1.1E-03 | 9.2E-04 | 7.1E-01 |
| 5% | 2.7E-05 | 1.1E-03 | 1.4E-03 | 7.3E-01 |
| 25% | 3.9E-05 | 2.4E-03 | 2.7E-03 | 8.1E-01 |
| 50% | 5.7E-05 | 3.8E-03 | 4.5E-03 | 9.2E-01 |
| 75% | 1.5E-04 | 5.7E-03 | 7.1E-03 | 9.7E-01 |
| 95% | 7.7E-04 | 1.3E-02 | 1.1E-02 | 1.0E+00 |
| Max | 8.4E-04 | 1.7E-02 | 1.1E-02 | 1.0E+00 |
| Count | 9 | 9 | 8 | 3 |

## CONCLUSIONS

TCE concentrations in all media (alluvial groundwater, soil gas, sub-slab vapor, and indoor air) showed substantial decreases (75-96%) over the 1998 to 2010 time frame, due to active groundwater remediation and natural attenuation. The decreases in the various media generally showed strong correlations.

The current study allowed a more detailed comparison of attenuation factors between media for one of the early datasets incorporated in the EPA Vapor Intrusion Database that was, and still is, one of the critical datasets cited for crawl space to indoor air attenuation factors. In addition, the 12 year history of paired deep soil gas sampling in conjunction with sub-slab, groundwater and indoor sampling allowed an evaluation of both the spatial and temporal variability of attenuation factors between all media, in a well-studied area.

The measured groundwater to indoor air and sub-slab vapor to indoor air attenuation factors for all of the homes in the study area were in the range of 2.6 $x10^{-5}$ to 8.4 $x10^{-4}$, and 9 $x10^{-4}$ to 1.1 $x10^{-2}$, which were within the $50^{th}$ to $75^{th}$ percentile of the values in the EPA 2010 Vapor Intrusion Database, well below the default attenuation factors of $10^{-3}$ and 0.1, respectively. These attenuation factors were consistent for the individual homes in all of the sampling events from 1998 to present.

The deep soil gas to indoor air attenuation factors were nearly identical to the sub-slab to indoor air attenuation factors in the adjacent homes (Figure 6). This demonstrates the ability of carefully sampled, deep soil gas to provide reasonable prediction of indoor air concentrations for adjacent homes.

### Acknowledgments

This Indoor Air Study Data Summary and Analysis Report was prepared in accordance with Consent Agreement No. 01-08-07-02 among Lowry Redevelopment Authority, Lowry Assumption, LLC (LAC) and the Colorado Department of Public Health and Environment. It is based on work performed by EnviroGroup Limited (EnviroGroup) and LAC in January and February 2010 and a review of analytical data from previous investigations.

## REFERENCES


1. EnviroGroup Limited. Indoor Air Study Work Plan, Former Lowry Air Force Base, Denver, Colorado, December 9, 2009.
2. Lowry Assumption, LLC. Results for the January 10 Semiannual Closure/Performance Groundwater Monitoring Program, Main TCE Plume, Operable Unit 5, Former Lowry Air Force Base, LAC, March 26, 2010.
3. Versar. Final Operable Unit 5 – Groundwater Remedial Investigation, Lowry Air Force Base, Colorado, Appendix K (Groundwater-To-Indoor Air VOC Migration Pathway Investigation Report), May 2001.
4. Versar. Revised Draft Final Phase III Groundwater-To-Indoor Air VOC Migration Pathway Investigation Report, June 2003.
5. Lowry Assumption, LLC. Final Supplemental Investigation Report Groundwater-To-Indoor Air, VOC Migration Pathway, Main TCE Plume, OU5, Former Lowry AFB, Denver, Colorado, October 2008.
6. Lowry Assumption, LLC. Final Phase 2 Corrective Action Plan for Groundwater Remediation at Lowry, December 21, 2006.
7. Lowry Assumption, LLC. Closure/Performance Groundwater Monitoring Program (GMP), Main TCE Plume, Operable Unit 5, June 20, 2007.
8. United States Environmental Protection Agency. *Compendium Method TO-15, Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially-Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry (GC/MS),* EPA/625/R-96/010b, Center for Environmental Research Information, Office of Research and Development, Cincinnati, Ohio, January, 1999.
9. United States Environmental Protection Agency. *OSWER Draft Guidance for Evaluation the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)*, EPA 530-D-02-004, November 2002.
10. Colorado Department of Public Health and Environment. Indoor Air Guidance, Draft, September 2004.
11. United States Environmental Protection Agency. *U.S. EPA's Vapor Intrusion Database and a Preliminary Evaluation of Attenuation Factors*, EPA 530-R-10-002, Office of Solid Waste, March 2010 Draft.
12. Kurtz, J.P., and D.J. Folkes. Background concentrations of selected chlorinated hydrocarbons in residential indoor air. In *Proceedings: Indoor Air 2002, the proceedings of the 9$^{th}$ International Conference on Indoor Air Quality and Climate*, Monterey, CA, June 30–July 5, 2002, p. 920-925.
13. Fitzgerald, N.A., and Fitzpatrick, J.J. An Evaluation of Vapor Intrusion Into Buildings Through a Study of Field Data. In Proceedings: *11$^{th}$ Annual Conference on Contaminated Soils*, University of Massachusetts, Amherst, October 1996.