

**Indoor Air Study Data Summary and Analysis Report  
Main TCE Plume, OU5  
Former Lowry Air Force Base  
Denver, Colorado**

Prepared by:

**EnviroGroup Limited  
Centennial, Colorado**

Prepared for:

**Lowry Assumption, LLC  
Denver, Colorado**

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## EXECUTIVE SUMMARY

Lowry Assumption, LLC (LAC) has been aggressively treating groundwater in the Northern Off-site Plume as part of the remediation of base-wide groundwater (Operable Unit 5 [OU5]) at the former Lowry Air Force Base (Lowry). This treatment has resulted in significant reductions of trichloroethylene (TCE) concentrations in groundwater plume-wide. As documented in the Phase 2 Corrective Action Plan for Groundwater Cleanup at Lowry (LAC 2006), this aggressive treatment was determined to be the best approach to protect human health and the environment and to mitigate any potential exposures to the public. Because the groundwater-to-indoor air pathway is the only potentially complete exposure pathway at the site, several studies, beginning in 1997, were performed to assess the impact of groundwater-derived TCE on indoor air and to evaluate the success of mitigation efforts under the Corrective Action Plan. The objectives of this study, which updates the evaluation of the mitigation efforts, are:

- to characterize the groundwater to indoor air pathway through sampling, and
- to evaluate whether observed decreases in groundwater VOC concentrations over time have resulted in similar decreases in VOC concentrations in indoor air, sub-slab, and soil vapor.

This report presents the results of the January 2010 sampling program and compares those results with historical data to evaluate trends and draw conclusions regarding the progress of remedial efforts, and the efficacy of using groundwater concentrations to assure protectiveness of the remedy. The data show strong correlations between the alluvial groundwater and indoor air TCE concentrations, (as well as soil gas and subslab concentrations) indicating that as groundwater concentrations decrease, there are comparable decreases in indoor air concentrations; thus the current remedy is shown to be effectively mitigating risks through the indoor air pathway. Remediation of the groundwater in the study area, in addition to natural attenuation of the contaminant, has resulted in decreases in average groundwater TCE concentration of approximately 90 percent (currently approximately 11 micrograms/liter [ $\mu\text{g/L}$ ], reduced from 110 in 1998-99) with an average concomitant decrease in indoor air concentrations of approximately 75%. Colorado Department of Public Health and Environment (CDPHE) has established risk management levels for TCE in indoor air in its Proposed Policy On Interim Risk Evaluation And Management Approach For TCE (2004), and these levels are used throughout this report as a point of reference. Seven of the nine homes tested have concentrations that are below mitigation action levels defined in the policy ( $0.8 \text{ micrograms per meters squared } [\mu\text{g/m}^3]$  - lowest action level at which mitigation may be recommended), and a decrease of as little as one  $\text{ug/L}$  in the groundwater TCE concentration is predicted to reduce annual average values in the remaining two homes to concentrations below CDPHE action levels

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## 1 INTRODUCTION

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 (CDPHE). 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.

LAC is currently remediating groundwater under an approved Corrective Action Plan (CAP) for base-wide groundwater (Operable Unit 5 [OU5]) at the former Lowry Air Force Base (Lowry). As approved in the CAP, the aggressive groundwater treatment being implemented was determined to be the best approach to protect human health and the environment and to mitigate any potential exposures to the public. As part of the remediation, a program to sample residential indoor air, outdoor air, sub-slab vapor, soil vapor, and groundwater was implemented in January 2010. The program, a follow-up to three previous investigations related to indoor air, 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.

### 1.1 SCOPE OF WORK

The scope of work was presented in EnviroGroup's Indoor Air Study Work Plan (Work Plan), dated December 9, 2009 (EnviroGroup, 2009), which was reviewed and approved by CDPHE on January 4, 2010. The 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 LAC. The program included sampling of up to 14 residences (including indoor air and sub-slab vapor) and the collection of up to 15 soil vapor samples from existing permanent soil vapor probes in the Study Area.

The timing of the Indoor Air Study coincided with the January 2010 OU5 Main TCE Plume closure/performance groundwater monitoring program (GMP) sampling. The groundwater data collected during the GMP have been used for the characterization of the groundwater-to-indoor air pathway presented in this report.

All investigation activities were conducted in accordance with the Work Plan to characterize indoor air quality conditions in the residences above the Main TCE Plume and were designed to support the ultimate closure of OU5.

## **1.2 REPORT ORGANIZATION**

The following sections of the report present background information (Section 2.0); investigation procedures (Section 3.0); laboratory procedures (Section 4.0); quality assurance/quality control (Section 5.0); investigation results (Section 6.0); and evaluation of the groundwater to indoor air pathway (Section 7.0); conclusions (Section 8.0); and references (Section 9.0).

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## 2 BACKGROUND INFORMATION

This section summarizes historical investigation observations, groundwater data, identifies the compounds of concern, and discusses background concentration considerations.

### 2.1 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, extended approximately three miles (at that time) to the north from source areas within the former base and passes under the study area, a residential area north of the base. The Headquarters Area and Fire Training Zone plumes are limited in areal extent and do not underlie any residential properties. Compared with average 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 90% (LAC, 2010b). This decrease resulted from the combination of interim remedial actions, active remediation, and natural degradation processes. Ongoing active remediation prior to this study included three full scale potassium permanganate injections that were performed in the study area in 2004, 2007, and 2009. Based on January 2010 groundwater data (LAC, 2010a) from samples collected in the study area, there have been additional reductions in the average TCE concentration of 56% within the study area since the previous indoor air study was performed in 2007.

The groundwater-to-indoor air migration pathway was studied as part of the OU5 investigation because of the potential risks from volatilization of VOCs dissolved in groundwater and the potential migration of these VOCs into overlying structures. During three previous investigations conducted in 1997-98, 2001, and 2007, the groundwater-to-shallow soil vapor pathway was investigated using a combination of groundwater, indoor air, outdoor air, sub-slab vapor, and soil vapor samples (Versar 2001, 2003 and LAC 2008). 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, as the concentrations in groundwater have decreased over time.

Following an initial indoor air sampling program conducted in September 1997 at the Heritage Estates apartments, located over the Main TCE Plume and immediately north of 11th Avenue, the Air Force installed active sub-slab depressurization (ASD) systems in all buildings at the complex that overlie the Main TCE Plume (Versar, 1999). In December 1997, the Air Force began an investigation to delineate areas where the groundwater-to-indoor air pathway was potentially complete (Versar, 2001 – Appendix

K). Eight of the 16 homes sampled in 1998 in the Versar 2001 study were tested again in one of the later studies, and six of these were sampled in the present study. The Phase III groundwater-to-indoor air study (Versar, 2003) 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. The data were used to assess health risks, regardless of confounding influences from indoor or outdoor sources or background. The groundwater exposure point concentration of  $1.4 \times 10^{-5}$  exceeded the target risk level at that time of  $1 \times 10^{-5}$  in one residence (1235 Uinta). The Air Force installed an ASD system in that residence and it began operation in March 2003, although the system was temporarily turned off during the 2007 sampling event. These data also demonstrated that indoor air concentrations were highest in the winter samples with concentrations twice the annual average (Versar, 2003, Table 5-1).

Active remediation of the OU5 groundwater plumes with a chemical oxidant (e.g., potassium permanganate) began in 2004 following treatability studies and the development of the Phase II Corrective Action Plan (Phase II CAP) (LAC, 2006). TCE was identified as the primary contaminant in the Lowry plumes; however, a full suite of VOCs are evaluated in the groundwater monitoring programs. 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, and additional treatment is currently ongoing. 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 (LAC 2010, pending RPASS). These percentages are based on using the initial versus the latest measured concentrations (as of January 2010) and the minimum versus maximum concentrations detected in the wells, respectively.

A follow-up indoor air study was implemented by LAC in 2007. The program was designed to assess whether or not observed decreases in dissolved VOC concentrations in groundwater have resulted in comparable decreases in VOC concentrations in soil vapor, sub-slab vapor, and indoor air. Fourteen residences between 12<sup>th</sup> and 13<sup>th</sup> Street were targeted for indoor air and sub-slab sampling, nine of which granted access. In that study a reduction in average groundwater concentrations of approximately 44% was observed, associated with reductions in the average 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. Further reductions in groundwater concentrations were observed in the study area following

groundwater treatment in the fall of 2007, and projections of indoor air reductions were made based on the ratios calculated in the 2007 study.

## **2.2 OPERABLE UNIT 5 GROUNDWATER STATUS**

A large amount of groundwater data have been collected in and around the Main TCE Plume under various investigation, remediation, and monitoring programs. Since the remediation of OU5 was privatized, LAC has collected groundwater data semi-annually from June 2003 through January 2010. Through December 2006, a semi-annual groundwater monitoring network of up to 70 wells was used for long-term monitoring and remediation performance monitoring of the three TCE groundwater plumes (LAC, 2004). In 2007, the semi-annual monitoring network was revised for the Main TCE Plume to create a Closure/Performance GMP network (LAC, 2007b) in order to support the eventual regulatory closure of the Main TCE Plume.

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, and data from these wells were used to develop the target analyte list used for the indoor air studies.

Alluvial groundwater 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 (Versar, 2001) and the semi-annual GMP reports. In the initial groundwater-to-indoor air pathway evaluation (Appendix K; Versar, 2001) the average alluvial TCE concentration based on data reported for 1996-1998 in the Study Area and the area immediately south (Heritage Estates) was 110 micrograms per liter ( $\mu\text{g/L}$ ). The average concentration in the 2007 study was 25  $\mu\text{g/L}$ , and the current average concentration (January 2010) is 11  $\mu\text{g/L}$ .

A summary of historical Investigation and Remediation activities is presented in Table 1.

**Table 1. Chronology of Investigation and Remediation Activities**

<b>Date</b>	<b>Activity</b>
June – November 1997	Initial pathway evaluation sampling (groundwater, soil gas, indoor air) of Heritage Estates and on-base buildings
December 1997 – January 1998	Installation of active sub-slab depressurization system at Heritage Estates
1998	OU5 RI groundwater-to-indoor air pathway evaluation
2000-2002	Phase 3 groundwater-to-indoor air contaminant migration pathway investigation
January 2003	Transition plan for groundwater cleanup and landfill closure at Lowry
March 2003	Installation of active sub-slab depressurization at residence UA03
2003	Phase 1 Corrective Action Plan (CAP) for groundwater remediation
2003	Treatability studies and Phase 2 CAP
Fall 2004	First round of potassium permanganate injections (on- and off-base)
Fall 2006	Second round of potassium permanganate injections (on-base)
March 2007	First LAC indoor air study
Fall 2007	Second round of potassium permanganate injections (off-base)
Spring 2008	Third round of potassium permanganate injections (on-base)
Summer/Fall 2009	Fourth and Third round of potassium permanganate injections (on- and off-base)
January - April 2010	Second LAC indoor air study and final site report

### 2.3 COMPOUNDS OF CONCERN

Ten compounds of concern (COCs) were selected as the target analytes for this investigation based on previous indoor air studies, as summarized in Table 2 below. These analytes include VOCs historically detected in groundwater samples in OU5 and potential degradation products of those compounds (Versar, 2003).

**Table 2. Compounds of Concern and Common Abbreviations**

Vinyl Chloride
1,1-Dichloroethene (1,1-DCE)
Trichloroethene (TCE)
Tetrachloroethene (PCE)
cis-1,2-Dichloroethene (cis-1,2-DCE)
trans-1,2-Dichloroethene (trans-1,2-DCE)
1,1-Dichloroethane (1,1-DCA)
1,2-Dichloroethane (1,2-DCA)
1,1,1-Trichloroethane (1,1,1-TCA)
1,1,2-Trichloroethane (1,1,2-TCA)

## 2.4 BACKGROUND CONSIDERATIONS

Investigations at other sites in the Denver Metropolitan Area and pertinent literature have demonstrated that some or all of the COCs present in the affected groundwater are routinely found in indoor air that is unaffected by VOCs in groundwater (Kurtz & Folkes, 2002; Foster, et.al., 2002; Kurtz et.al. 2010). Many of these constituents are also found in outdoor air. Potential sources of these constituents include, but are not limited to: consumer products, dry cleaned clothes, building materials, and industrial, commercial and residential uses of chemicals or products that result in releases of VOCs to the indoor and ambient air. For the purpose of this investigation, VOCs present from these non-groundwater sources are considered “background”.

The investigation procedures used during implementation of the Work Plan were designed to identify impacts from background concentrations of the constituents in indoor air. Residents were interviewed regarding product use in their home and requested to limit uses of VOC-containing substances during the sampling period. Concentrations of VOCs in outdoor air were measured concurrently with indoor air measurements to identify baseline conditions. COCs detected in indoor air, but not detected in sub-slab vapor and soil vapor, may also be used to define background contributions. EnviroGroup has used a line-of-evidence approach to evaluate background contributions to indoor air results.

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## 3 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 the project Quality Assurance/Quality Control (QA/QC) Plan and Health and Safety Plan (HASP).

### 3.1 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 (Versar, 2001 and 2003; LAC, 2008). 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 (LAC, 2008). 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. The two homes at 1264 and 1268 Uinta 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.

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. Crawl space samples were collected from three of the homes. 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.

#### 3.1.1 Contacting Candidate Residences

Property owner contact information for the 14 candidate residences was obtained from the Denver County Assessor's office. A letter, reviewed and approved by LAC, requesting participation in the indoor air study was sent to each property owner with a postage paid post card. If the owner did not respond, a second letter was hand delivered. For any owners that did not respond, attempts were made to speak with the owner personally or by phone. As during the March 2007 study, permission was obtained to collect

indoor air and sub-slab vapor samples at nine of the 14 candidate residences (but not at all of the same residences). The owners of three homes (1264 Uinta, 1268 Uinta, and 1329 Uinta) denied access while no response was received from the owners of the remaining two homes (1271 Uinta and 1314 Ulster).

### **3.1.2 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.

During sampling activities, each residence was inspected for an existing radon mitigation system and the status of that system, if applicable. The radon mitigation system at 1235 Uinta was turned off approximately one week prior to indoor air sampling. The completed questionnaire, floor plan sketch, and chemical inventory for each residence are provided in Appendix A.

## **3.2 INDOOR AND OUTDOOR AIR SAMPLING PROCEDURES**

A minimum of two indoor air samples and one sub-slab vapor sample were collected from nine of the 14 candidate residences. A total of nine indoor air samples from the 1<sup>st</sup> floor, 11 indoor air samples from basements, and three indoor air samples from crawl spaces were collected from nine residences. These numbers also include samples collected during resampling of the basement at 1282 Uinta Street. This home was resampled because the initial sub-slab sample result yielded all non-detectable concentrations and was thus considered suspect. Resampling required paired sub-slab and indoor air measurements.

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. In addition, one outdoor air sample was collected for each day of indoor air sampling, contemporaneous with indoor air sampling, for comparison to the indoor air results. Due to a shortage of sampling containers, no outdoor air samples were collected on January 27 or February 23 in conjunction with the indoor air sampling at 1350 Ulster and resampling at 1282 Uinta, respectively. The outdoor air samples were collected immediately outside the buildings (i.e., not closer than 5 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. A total of five outdoor air samples were collected.

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 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, with three exceptions. The final canister vacuum in sample LAI02 was equal to -0.18 inches Hg, the final canister vacuum in sample LAI23 was equal to -0.91 inches Hg, and the final canister vacuum in sample LAI09 was equal to 0 inches Hg. For the latter sample, the sampling duration may have been less than 24 hours.

Samples were shipped to the laboratory within three days of sampling so that no sample exceeded the 30-day holding time for the TO-15 method. Full chain of custody documentation was maintained for all canisters from time of shipping from the laboratory to the time of analysis. Historical and current indoor air sample locations are shown on Figure 1.

### **3.3 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. One additional sample was collected during resampling of the sub-slab vapor at 1282 Uinta Street. 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, on the lowest floor of the residence. Temporary probes were installed by drilling approximately 1/2 or 3/4 inch outer diameter (OD) holes through the basement or first 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 Nylaflo® 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 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.

Samples were shipped to the laboratory within three days of sampling so that no sample exceeded the 30-day holding time for the TO-15 method. Full chain of custody documentation was maintained for all canisters from time of shipping from the laboratory to the time of analysis. Historical and current sub-slab vapor sample locations are shown on Figure 1. Sub-slab vapor collection information is summarized on the Sub-slab Vapor Sample Collection Logs provided in Appendix B.

### **3.4 SOIL VAPOR PROBE INSTALLATION AND SAMPLING PROCEDURES**

In cases where a damaged or missing soil vapor point was indentified, a replacement soil vapor point was installed by LAC prior to the indoor air study as follows. 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 sampling tube (i.e., 1/4 inch) with a 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. Two soil vapor probes (i.e., SGCA07 and SGCA19) were replaced by LAC prior to sampling activities.

Soil vapor samples were collected using current state of the art procedures. During soil vapor sampling activities, a clean, small plastic or stainless steel shroud with two small ports was placed over each soil 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 existing soil vapor probe tube, which was fitted with a metallic Swagelok® fitting, was extended above ground surface with a clean length of Nylaflo® tubing and fitted with an air-tight valve. All connections were made inside/beneath the shroud to verify that the connections/seals were air-tight.

Each soil 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, soil vapor probes were purged (i.e., up to 1.0 L) 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. 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 soil vapor 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 soil vapor sample was collected for analysis. Upon completion of sampling activities, all soil vapor probes were closed and secured.

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 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.

Samples were shipped to the laboratory within three days of sampling so that no sample exceeded the 30-day holding time for the TO-15 method. Full chain of custody documentation was maintained for all canisters from time of shipping from the laboratory to the time of analysis. Soil vapor sample locations are shown on Figure 1. Soil vapor collection information is summarized on the Soil Vapor Sample Collection Log provided in Appendix B.

### **3.5 GROUNDWATER SAMPLE COLLECTION**

Groundwater samples from 13 monitoring wells (ten alluvial and three in the Denver Formation) were collected within the Study Area to assess the current concentrations of COCs. Two wells (i.e., MWCA13 and IM-9) were destroyed after the 2007 indoor air study and were replaced by LAC prior to January 2010 sampling activities. Groundwater samples from 13 monitoring wells were collected by LAC personnel as part of the January 2010 OU5 Main TCE Plume Closure /Performance GMP and the alluvial well samples have been used to assess the relationship between changes in VOC concentrations in groundwater and indoor air, sub-slab vapor, and soil vapor samples.

Groundwater samples were analyzed for VOCs by EPA Method 8260B, following the procedures set forth in the GMP work plans. Monitoring well locations are shown on Figure 1.

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## 4 LABORATORY PROCEDURES

This section presents a summary of laboratory procedures for indoor air, outdoor air, sub-slab vapor, soil vapor, and groundwater samples.

### 4.1 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 (USEPA, 1999a), for the 10 COCs indicated in Table 2, by Air Toxics, Inc. using internal standard operating procedures (SOPs). Specific analytical procedures are described below.

The laboratory reporting limits (RLs) are initially established for an undiluted laboratory standard. When a sub-atmospheric integrated sample is collected, the canister does not fill completely. A diluent gas is added to pressurize the canisters for analysis. Consequently, sample RLs can vary for each sample, depending on sample volume and sample matrix effects, as shown on Table 3.

RLs for the study are low enough for comparison to CDPHE policy action levels and/or levels that have been used at other sites in Colorado. They are the best available CDPHE-approved values for evaluating risks to human health from indoor air. The RL for TCE in indoor air is less than the 0.8 micrograms per cubic meter ( $\mu\text{g}/\text{m}^3$ ) residential action level in the CDPHE's 2004 TCE interim policy, and is also well within the range of typical background air. The RL for PCE in indoor air is well below the residential action level of 15.5  $\mu\text{g}/\text{m}^3$  CDPHE 2006). The 0.8  $\mu\text{g}/\text{m}^3$  TCE and 15.5  $\mu\text{g}/\text{m}^3$  PCE action levels are defined in the respective policies as the level at which mitigation may be required if a subsurface source is indicated and below which continued monitoring would not be required. All indoor air RLs for other COCs are below the CDPHE action levels established for the Redfield Rifle Scope Site. The Redfield Site action levels are comparable to those used at other sites in Colorado and provide the best guidelines for comparison.

Sub-slab vapor and soil vapor RLs are considered to be acceptable, considering the minimum 100 fold attenuation observed between historical sub-slab vapor and paired indoor air samples in the Study Area. For TCE, the sub-slab and soil vapor 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.

**Table 3. Sample Reporting Limits for Air and Vapor Samples**

<b>Volatile Organic Compound</b>	<b>Indoor/Outdoor Air Sample RL (µg/m<sup>3</sup>)</b>	<b>Soil Vapor and Sub-Slab Vapor Sample RL (µg/m<sup>3</sup>)</b>	<b>CDPHE Action Level (µg/m<sup>3</sup>)</b>
Vinyl Chloride	0.039 to 0.073	5.7	0.72
1,1-Dichloroethene (1,1-DCE)	0.06 to 0.11	5.7	5.0
Trichloroethene (TCE)	0.027 to 0.046	7.8 (MDL=1.12)	0.8**
Tetrachloroethene (PCE)	0.21 to 0.39	9.8 (MDL=1.02)	15.5***
cis-1,2-Dichloroethene (cis-1,2-DCE)	0.12 to 0.22	5.7	NA
trans-1,2-Dichloroethene (trans-1,2-DCE)	0.6 to 1.1	5.7	NA
1,1-Dichloroethane (1,1-DCA)	0.062 to 0.12	5.8	510
1,2-Dichloroethane (1,2-DCA)	0.062 to 0.12	5.8	0.69
1,1,1-Trichloroethane (1,1,1-TCA)	0.16 to 0.31	7.9	1000
1,1,2-Trichloroethane (1,1,2-TCA)	0.16 to 0.31	7.9	NA

Notes:

Residential Action Levels from the July 31, 2007 Hazardous Communication letter for the Redfield Site

\*\*CDPHE, 2004 and Redfield letter (2007)

\*\*\*CDPHE, 2006 and Redfield letter (2007)

MDL = Minimum detection limit, RL = Reporting Limit. Any concentrations between the MDL and the RL were reported as an estimated concentration.

NA = Not Applicable.

## 4.2 GROUNDWATER SAMPLES

Laboratory analysis for groundwater samples were completed in accordance with the GMP work plans, using EPA Method 8260B. The maximum reporting limits are provided in Table 4 and are at or below the Colorado Basic Standards for Groundwater (CBSGW),

**Table 4. Sample Reporting Limits for Groundwater**

<b>Volatile Organic Compound</b>	<b>Sample Reporting Limits (µg/L)</b>	<b>CBSGW* (µg/L)</b>
Vinyl Chloride	2	2
1,1-Dichloroethene (1,1-DCE)	2	7
Trichloroethene (TCE)	2	5
Tetrachloroethene (PCE)	2	5
cis-1,2-Dichloroethene (cis-1,2-DCE)	2	70
trans-1,2-Dichloroethene (trans-1,2-DCE)	2	100
1,1-Dichloroethane (1,1-DCA)	2	NA
1,2-Dichloroethane (1,2-DCA)	2	5
1,1,1-Trichloroethane (1,1,1-TCA)	2	200
1,1,2-Trichloroethane (1,1,2-TCA)	2	5

Notes:

\*CBSGW – Colorado Basic Standard for Groundwater.

NA = Not Applicable.

## 5 QUALITY ASSURANCE/QUALITY CONTROL

This section addresses quality control issues associated with field and laboratory investigations for indoor air, outdoor air, sub-slab vapor, soil vapor, and groundwater. 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 and required for the performance of monitoring obligations, the evaluation of remedial alternatives, and the design of remedies.

### 5.1 LABORATORY QA/QC REQUIREMENTS

Laboratory QA/QC analytical results were reviewed during data validation. Results indicated acceptable accuracy and precision in the analyses.

The two laboratory duplicates for soil vapor yielded excellent agreement for the two compounds detected above reporting limits (TCE and PCE), with Relative Percent Differences (RPDs) of less than 14%.

The two laboratory duplicates for sub-slab vapor yielded excellent agreement for the one compound detected above reporting limits (TCE), with RPDs of less than 4%.

Laboratory duplicates for indoor air generally yielded excellent agreement for the three compounds detected above reporting limits (TCE, PCE and 1,2-DCA), with RPDs of less than 5%, except for one of the three lab duplicates where the RPD for 1,2-DCA was 34%. The 1,2-DCA results for this sample pair were just slightly above the reporting limit and larger variability is to be expected at these low concentrations.

### 5.2 FIELD QA/QC REQUIREMENTS

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.

#### 5.2.1 Trip Blanks

Trip blanks were not submitted for the soil vapor, sub-slab vapor or indoor air sampling program because the laboratory selected used individually certified clean Summa canisters and flow

regulators. Trip blanks were not considered to be necessary when such cleaning certification was provided.

### **5.2.2 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” arrangement. Field duplicates are prepared to evaluate sampling technique and laboratory procedures through the analysis of representative samples obtained from a relatively homogenous medium. 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 the two compounds detected above reporting limits (TCE and PCE), with Relative Percent Differences (RPDs) of 40% to 50.5%.

The four field duplicates for sub-slab vapor yielded excellent agreement for the one compound detected above reporting limits (TCE), with RPDs of less than 15%.

Field duplicates for indoor air generally yielded excellent agreement for the three compounds detected above reporting limits (TCE, PCE and 1,2-DCA), with RPDs of less than 22%, except for one of the two field duplicates where the RPD for 1,2-DCA was 56%. The 1,2-DCA results for this sample pair were just slightly above the reporting limit and larger variability is to be expected at these low concentrations.

The field duplicates for groundwater yielded identical results for the one compound detected above reporting limits (TCE).

### **5.2.3 Ambient Air**

Twenty-four hour ambient air (i.e., outdoor air) samples were to be collected during each day of indoor air sampling, contemporaneous with the indoor air sampling, for comparison to the indoor air results. Five outdoor air samples were collected during the investigation. Due to the extended time frame of indoor air sampling, Summa canisters were unavailable for outdoor air sampling on two days when indoor air samples were collected. The five outdoor air samples collected are considered to be adequate to represent the range of outdoor air VOC concentrations during the indoor air sampling program.

#### **5.2.4 Canister Vacuums**

Initial field vacuums should be greater than 24 inches Hg 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 low 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 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 duplicate at this location, the higher TCE concentration from the duplicate was used for comparison purposes. Sample LAI08 from the basement of 1238 Uinta 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.

### **5.3 DATA VALIDATION**

Laboratory analytical data were validated and verified in terms of their ability to satisfy the data quality objectives for accuracy, precision and completeness specified by the project QA/QC Plan and the analytical laboratory. Data validation was completed by trained EnviroGroup personnel who were not involved with the sample collection. Validation flags applied to the results are explained in the footnotes to each table.

## 6 INVESTIGATION RESULTS

This section summarizes the results of the indoor air, outdoor air, sub-slab vapor, soil vapor, and groundwater investigations conducted as part of this Indoor Air Study.

### 6.1 INDOOR AIR INVESTIGATION

This section presents the results of the January 2010 indoor air, outdoor air, and sub-slab vapor sampling in the study area.

#### 6.1.1 Indoor Air Analytical Results

The results from indoor air samples collected by EnviroGroup from nine homes in January 2010 are shown on Figure 2 and in Table 5. Of the ten indoor air COCs analyzed, six were detected (all except 1,1,2-TCA, cis-1,2-DCE, trans-1,2-DCE and 1,1-DCE) in one or more samples. As with previous sampling, TCE and PCE were the dominant VOCs present in indoor air, with TCE concentrations ranging from 0.053 to 1.7  $\mu\text{g}/\text{m}^3$  and PCE from 0.24 to 6.6  $\mu\text{g}/\text{m}^3$ .

Trace levels of 1,1,1-TCA similar to those in outdoor air were present in all samples. Low levels of vinyl chloride were detected in samples from three homes (1238 Uinta, 1330 Ulster, and 1222 Uinta). One low level detection of 1,1-DCA, in the basement sample from 1222 Uinta, is considered anomalous. All indoor air samples except one had detectable results for 1,2-DCA, with concentrations ranging from 0.068 to 0.68  $\mu\text{g}/\text{m}^3$ . Most samples had 1,2-DCA concentrations similar to outdoor air, except the first floor samples from 1330 Ulster, 1235 Valentia, and 1350 Ulster. In all three of these cases the first floor results were substantially larger than those for the basement or crawl space. The average TCE concentration in the 11 basement indoor air samples was 0.395  $\mu\text{g}/\text{m}^3$ . Note that only two homes (1282 Uinta and 1238 Uinta) had basement TCE concentrations above 0.33  $\mu\text{g}/\text{m}^3$ . The average PCE concentration in the 11 basement indoor air samples was 0.92  $\mu\text{g}/\text{m}^3$ .

The average TCE concentration in the nine first floor indoor air samples was 0.394  $\mu\text{g}/\text{m}^3$ . The average PCE concentration in the nine first floor indoor air samples was 0.71  $\mu\text{g}/\text{m}^3$ . Most of the homes sampled had PCE concentrations similar to outdoor air, with a few exceptions. Note that at 1353 Uinta Street, the PCE in the basement sample was substantially larger (more than 4 times higher) than the result for the crawl space or for the first floor. This strongly suggests an indoor

source, consistent with the storage of numerous paints and some spot removers in this basement (see Appendix A). Likewise, at 1282 Uinta Street, the January 19<sup>th</sup> first floor sample had substantially higher (more than 4 times higher) PCE than the crawl space or basement sample. This also strongly suggests an indoor source. For TCE, the first floor indoor air results were 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.

The average TCE concentration in the three crawl space indoor air samples was  $0.46 \mu\text{g}/\text{m}^3$ . The average PCE concentration in the three crawl space indoor air samples was  $0.57 \mu\text{g}/\text{m}^3$ . For the three locations with crawl space data, the basement and first floor TCE results were very comparable to the crawl space results, suggesting minimal attenuation from crawl space to indoor air.

### **6.1.2 Outdoor Air Analytical Results**

The results from outdoor air samples collected by EnviroGroup from the vicinity of five homes in January 2010 are shown in Table 5. Of the ten indoor air COCs analyzed, only four were detected (1,1,1-TCA, 1,2-DCA, PCE and TCE) in one or more samples. As with previous sampling, PCE was the dominant VOC present in outdoor air, with concentrations ranging from  $0.23$  to  $0.49 \mu\text{g}/\text{m}^3$ , similar to that in most of the homes tested. The average PCE concentration in these samples was  $0.33 \mu\text{g}/\text{m}^3$ . TCE concentrations ranged from  $0.029$  to  $0.089 \mu\text{g}/\text{m}^3$ , with an average of  $0.052 \mu\text{g}/\text{m}^3$ . Trace levels of 1,1,1-TCA (average of  $0.046 \mu\text{g}/\text{m}^3$ ) and 1,2-DCA (average of  $0.11 \mu\text{g}/\text{m}^3$ ) were also consistently present.

### **6.1.3 Sub-Slab Vapor Analytical Results**

The results from sub-slab vapor samples collected by EnviroGroup from nine homes in January 2010 are shown on Figure 3 and in Table 6. Of the ten indoor air COCs analyzed, only two were detected (PCE and TCE) in one or more samples. As with previous sampling, TCE was the dominant VOC present in sub-slab vapor, with concentrations ranging from below detection ( $< 1.1 \mu\text{g}/\text{m}^3$ ) to  $260 \mu\text{g}/\text{m}^3$ . The average TCE concentration in these 9 sub-slab vapor samples was  $84 \mu\text{g}/\text{m}^3$ . PCE concentrations were all below  $25 \mu\text{g}/\text{m}^3$  in these samples, and were typically about 10% of the associated TCE concentration.

## 6.2 SOIL VAPOR INVESTIGATION

The results from soil vapor samples collected by EnviroGroup from 15 permanent, deep (eight to ten foot) soil vapor points in January 2010 are shown on Figure 4 and in Table 7. Of the ten indoor air COCs analyzed, only six were detected (1,1-DCE; 1,1,1-TCA; 1,2-DCA; cis-1,2-DCE, PCE and TCE) in one or more samples. As with previous sampling, TCE was the dominant VOC present in soil gas, with concentrations ranging from below detection ( $< 7.6 \mu\text{g}/\text{m}^3$ ) to  $1200 \mu\text{g}/\text{m}^3$ . The average TCE concentration in these 15 soil vapor samples was  $218 \mu\text{g}/\text{m}^3$ . PCE concentrations were all below  $120 \mu\text{g}/\text{m}^3$  in these samples, and were typically about 10% of the associated TCE concentration. A few of the samples with the higher TCE concentrations yielded trace (below reporting limit) concentrations of 1,1-DCE, cis-1,2-DCE and 1,1,1-TCA. One sample, EG-SGCA-11, yielded trace levels of 1,2-DCA. This sample is suspected of sampling canister leakage during shipment to the laboratory, therefore the 1,2-DCA result is suspect.

## 6.3 GROUNDWATER INVESTIGATION

The results from groundwater samples collected by another LAC contractor in January 2010 are presented in Table 8 and Figure 5. Of the ten indoor air COCs analyzed, only three were detected (cis-1,2-DCE, PCE and TCE) in one or more samples. As with previous sampling, TCE was the dominant VOC present in groundwater, with concentrations ranging from below detection ( $< 2 \mu\text{g}/\text{L}$ ) to  $32 \mu\text{g}/\text{L}$  in alluvial groundwater. The average TCE concentration in the ten alluvial wells was  $11 \mu\text{g}/\text{L}$ .

PCE concentrations were all below detection in the ten alluvial wells, consistent with its low abundance relative to TCE. PCE and cis-1,2-DCE were only detected in one deep (Denver Formation) bedrock well (of a nested well pair) at levels below the MCLs.

## 7 GROUNDWATER-TO-INDOOR AIR PATHWAY EVALUATION

This section presents an evaluation of the groundwater-to-indoor air, or vapor intrusion, pathway including a comparison of indoor air concentrations to screening levels (Section 7.1), a comparison of indoor air to background concentrations (Section 7.2), a comparison of indoor air to subsurface concentrations (Section 7.3), an evaluation of current and historical attenuation factors between indoor air and other media (Section 7.4), and a trend analysis of all groundwater, soil gas, sub-slab vapor and indoor air results for TCE (Section 7.5).

### 7.1 INDOOR AIR VS SCREENING LEVELS

CDPHE has established risk management levels for TCE in indoor air in their Proposed Policy On Interim Risk Evaluation And Management Approach For TCE (2004), and these levels are used throughout this report as a point of reference for understanding the effectiveness of the remediation program. This section presents comparisons of indoor air (including crawl space) concentrations to available CDPHE residential action levels in order to provide context for the results. As described in Section 4.1, these values are the best available for evaluating risks in indoor air. All indoor air results for 1,1-DCE, 1,1-DCA, 1,1,1-TCA, 1,2-DCA, PCE, trans-1,2-DCE, and vinyl chloride were well below CDPHE action levels shown in Table 3. Similarly, all results for 1,1,2-TCA were non-detectable.

Two homes (1238 and 1282 Uinta Street) have TCE results above the CDPHE action level of  $0.8 \mu\text{g}/\text{m}^3$ . These samples were collected during the winter, and therefore most likely represent the maximum annual indoor air concentration. As noted in Section 2.1, based on the seasonal (bimonthly) sampling at several of these homes in 2000-2001, winter indoor air concentrations are approximately twice the annual average concentration in a home (see table 5-1 of Versar, 2003). For long-term exposure estimates (30 years) the annual average is a more representative exposure concentration. Based on the Versar data, the resulting calculated current annual average TCE concentrations at the two homes with the highest TCE results in 2010 (1238 and 1282 Uinta) would be  $0.85 \mu\text{g}/\text{m}^3$  and  $0.55 \mu\text{g}/\text{m}^3$ , respectively.

### 7.2 INDOOR VS BACKGROUND CONCENTRATIONS

This section presents comparisons of indoor air to background concentrations, including outdoor air and background indoor air data.

### **7.2.1 Indoor Air to Outdoor Air Concentration Comparison**

The indoor air TCE results for 1330 Ulster, 1305 Uinta, 1235 Valentia, and 1350 Ulster are only marginally higher than the outdoor air TCE concentrations (average of  $0.052 \mu\text{g}/\text{m}^3$ ), 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.

Except for the anomalously high first floor results at 1282 Uinta and 1353 Uinta, and the anomalous basement PCE result at 1353 Uinta, the indoor air PCE results are nearly identical to the outdoor air PCE results for five of the remaining six homes. The PCE results at 1238 Uinta are slightly above those in outdoor air. Only the home at 1238 Uinta appears to have any measurable vapor intrusion contribution to indoor air PCE concentrations, although these concentrations are well below the CDPHE action levels.

As noted previously, the majority of the 1,2-DCA results in indoor air are similar to the outdoor air results with a few homes having indications of indoor sources. Trace levels of 1,1,1-TCA, similar to those in outdoor air, are present in all samples.

### **7.2.2 Indoor Air to Background Indoor Air Comparison**

Low levels of vinyl chloride occur in samples from two homes (1238 Uinta and 1222 Uinta). These low concentrations are typical of background indoor sources (Kurtz and Folkes, 2002; Foster and others, 2002a). One low level detection of 1,1-DCA, in the basement sample from 1222 Uinta, is considered anomalous. All except one indoor air sample had detectable results for 1,2-DCA, with concentrations ranging from  $0.068$  to  $0.68 \mu\text{g}/\text{m}^3$ . Most samples had 1,2-DCA concentrations similar to outdoor air, except for the first floor samples from 1330 Ulster, 1235 Valentia, and 1350 Ulster. In all three of these cases the first floor results were substantially larger than those for the basement or crawl space. This suggests an indoor source for 1,2-DCA consistent with recent findings about indoor sources for 1,2-DCA (Kurtz et.al., 2010). Note that, with one exception, 1,2-DCA is not present in soil vapor or sub-slab vapor, and it has not been detected in alluvial groundwater.

The three anomalously high PCE results (from  $1.5$  to  $6.6 \mu\text{g}/\text{m}^3$ ) are comparable to typical background indoor air ranges (Kurtz and Folkes, 2002; Foster and others, 2002a). Note that at 1353 Uinta Street, the PCE in the basement sample is substantially larger than the result for the crawl space or for the first floor. This strongly suggests an indoor source consistent with the numerous products stored in the basement of this home (Appendix A). Likewise, at 1282 Uinta

Street, the January 19<sup>th</sup> first floor sample had substantially higher PCE than the crawl space or basement sample. This also strongly suggests an indoor source. Note that PCE has not been detected in alluvial groundwater wells in the study area.

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. Most of the TCE results are consistent with background indoor air levels (Foster and others, 2002b), except for those at 1238 Uinta and 1282 Uinta. The latter two homes are the only homes with an apparent vapor intrusion contribution of TCE above typical background levels.

The home at 1238 Uinta is the only one with an apparent slight vapor intrusion contribution to PCE, although the results (0.45 and 0.53  $\mu\text{g}/\text{m}^3$ ) are well within typical background indoor air ranges and the maximum possible vapor intrusion contribution is substantially less than the CDPHE action level of 15.5  $\mu\text{g}/\text{m}^3$ .

## **7.3 INDOOR AIR VS SUBSURFACE CONCENTRATIONS**

As an essential part of the groundwater-to-indoor air pathway evaluation this section compares indoor air concentrations to sub-slab vapor, soil vapor, and groundwater concentrations. In addition, sub-slab vapor concentrations are compared to nearby soil vapor concentrations.

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

The two homes with the highest indoor air concentrations of TCE (1282 Uinta and 1238 Uinta) also have the highest sub-slab vapor concentrations of TCE. Likewise, with the exception of 1235 Uinta, the three homes with the lowest indoor air TCE concentrations (1330 Ulster, 1305 Uinta, and 1350 Ulster) also have the lowest sub-slab vapor TCE concentrations. The sub-slab TCE is not detectable at 1350 Ulster, suggesting that the measured indoor air TCE at this home is completely due to background sources (probably largely outdoor air in this case). The homes at 1222 Uinta, 1235 Uinta, and 1353 Uinta all have slightly elevated indoor air TCE levels (ranging from 0.14 to 0.33  $\mu\text{g}/\text{m}^3$ ), with higher concentrations in the basement than on the first floor. This suggests a potential sub-surface source for TCE. The sub-slab to indoor air attenuation factors for 1222 Uinta and 1235 Uinta are consistent with historical values at these two homes, when sub-slab concentrations were higher than at present, suggesting that a minor vapor intrusion contribution to TCE is present in these two homes. However, the apparent sub-slab to indoor air attenuation for the 2010 result at 1353 Uinta 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.

As noted previously, PCE concentrations in the sub-slab were all below  $25 \mu\text{g}/\text{m}^3$ , and were typically about 10% of the associated TCE concentration. Based on a simple ratio comparison, one would expect about 10% as much PCE in indoor air as TCE, if the source were vapor intrusion. Based on the measured indoor air TCE concentrations, the maximum vapor intrusion contribution to PCE (at 1238 Uinta) would be approximately  $0.17 \mu\text{g}/\text{m}^3$ , well below the screening level of  $15.5 \mu\text{g}/\text{m}^3$ . All other indoor air locations would be predicted to have a negligible vapor intrusion contribution to PCE.

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

The two homes with the highest indoor air concentrations of TCE (1282 Uinta and 1238 Uinta) are proximal to two of the four soil vapor locations (near homes) with the highest TCE concentrations. Likewise, with the exception of 1235 Uinta, the five homes with the lowest indoor air TCE concentrations (1330 Ulster, 1305 Uinta, 1350 Ulster, 1353 Uinta, and 1235 Valentia) also have the lowest nearby soil vapor TCE concentrations. The indoor air results for 1222 Uinta 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 1235 Uinta 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.

As noted previously, PCE concentrations in the soil vapor in the immediate vicinity of homes (excluding SGCA-06) were all below  $70 \mu\text{g}/\text{m}^3$ , and were typically about 10% of the associated TCE concentration, similar to the sub-slab vapor results.

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

The two homes with the highest sub-slab vapor concentrations of TCE (1282 Uinta and 1238 Uinta) are proximal to two of the four soil vapor locations (near homes) with the highest TCE concentrations. The sub-slab TCE at these two homes has the same concentration as the nearby soil vapor, within a factor of two. The sub-slab TCE results for 1222 Uinta are intermediate between the concentrations in surrounding soil vapor. The sub-slab results for 1350 Ulster are

lower than the nearby soil gas point (SGCA10), but this home may be beyond the edge of the plume based on the historical near absence of TCE in the sub-slab at this home. The sub-slab TCE results for 1235 Valentia are substantially higher than that in the two nearby soil vapor points, although the nearby alluvial groundwater has comparable TCE concentrations to those near other homes tested. The historical data for this location in 1998 yielded low indoor air and very low sub-slab TCE concentrations suggesting that higher soil gas concentrations may have diffused towards this location since 1998. The sub-slab TCE results for 1235 Uinta are anomalously 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 anomalously 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.

#### **7.3.4 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. 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. This unclear spatial relationship between concentrations in the two media is likely due to groundwater response to remedial treatment with insufficient time for the effects to diffuse to the sub-slab and then indoor air. The closer correspondence of soil vapor and sub-slab vapor may be a reflection of this time lag for diffusion from the water table.

PCE was not detected in any of the groundwater samples collected from the ten alluvial wells in the Study Area. Based on the above, no significant vapor intrusion-derived PCE would be expected in indoor air.

### **7.4 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.

#### **7.4.1 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  $1.1 \times 10^{-2}$ , and average  $5.3 \times 10^{-3}$  (Table 9). 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 9, with the exception of the 1998 results for 1235 and 1329 Uinta. 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. This finding of anomalously low indoor air concentrations is consistent with the open house sampling conditions documented for these two homes in the 1998 sampling event (Versar, 2001 Table 6-14). Note that the range of 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, but are comparable to the median sub-slab to indoor air attenuation factor in the 2010 EPA VI database.

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

Attenuation factors for TCE in soil vapor points nearest the homes compared to indoor air from the January 2010 sampling event range from  $1.1 \times 10^{-3}$  to  $1.7 \times 10^{-2}$  (Table 10), 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 10. The one location with the lowest apparent attenuation (1235 Valentia) is anomalous in that the sub-slab vapor TCE concentration is nearly twenty times higher than the nearby soil gas concentration. It should be noted that the indoor air TCE results at this home are only slightly greater than the outdoor air TCE and are well within the range of typical indoor air background (Kurtz and Folkes, 2002; Foster and others, 2002). No measurable vapor intrusion related TCE appears to be present in the indoor air at this home.

### 7.4.3 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  $\mu\text{g}/\text{m}^3$  from  $\mu\text{g}/\text{L}$ . These calculated equilibrium soil gas concentrations (at the water table) can be directly compared 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  $8.25 \times 10^{-2}$  (Table 11). Similar results were found for the 2007 paired groundwater and soil gas sampling event (Table 11).

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 attenuation in the vadose zone. Many sites report similar findings of approximately 10% of the expected equilibrium soil gas concentration for deep soil gas samples.

### 7.4.4 Attenuation from Groundwater to Indoor Air

Attenuation factors for TCE in groundwater-derived vapor compared to that measured in indoor air from the January 2010 sampling event range from  $2.6 \times 10^{-5}$  to  $8.4 \times 10^{-4}$ , with an average of  $2 \times 10^{-4}$  (Table 12). These ranges are very similar to those determined from previous groundwater and indoor air sampling events (Table 12). The average groundwater to indoor air attenuation factor is nearly an order of magnitude less than the 2002 EPA default attenuation factor of  $10^{-3}$ , but is approximately equivalent to the 75<sup>th</sup> percentile of the 2010 EPA VI Database attenuation factor for groundwater to indoor air and essentially equivalent to the median attenuation for the coarser soil types in the EPA Database.

## 7.5 TREND ANALYSIS

Groundwater remediation activities over the past six years have resulted in substantial reductions in VOC concentrations in alluvial groundwater in this area. The average TCE concentration in the ten alluvial wells was  $11 \mu\text{g}/\text{L}$  in January 2010 versus  $25 \mu\text{g}/\text{L}$  for the ten alluvial wells sampled in 2007 and approximately  $110 \mu\text{g}/\text{L}$  for the two center plume alluvial wells in existence in 1996-2001. A comparison just for the two center plume alluvial wells in existence in 1996-2001 (MWOB04 and MWOB21) to data for 2010 yields identical results for the average

concentrations at different time periods. All media have shown substantial reductions in VOC concentrations since 1998 and are discussed more fully below.

### **7.5.1 Groundwater Concentration Trends over Time**

Time-concentration trends for TCE for the individual wells are shown overlain in Figure 6. From 2001 to 2007 average groundwater TCE concentrations decreased approximately 60% for the two alluvial wells tested in both events (Table 13). From 2007 to 2010 average groundwater TCE concentrations were reduced approximately 57% for the ten alluvial wells sampled in both events. The reductions typically ranged from 50% to 75% for these wells. However, three wells showed increased concentrations in 2010 compared to 2007 (MWOB22 [MWOB22R], IM-9 [MWCM14], and B-1), although these increases were generally small ( $< 8.0 \mu\text{g/L}$ ). For two wells, MWOB22R and MWCM14, this could be due to lithologic variations over the screen intervals of the relocated wells. For two of the three alluvial wells with data from 1998 to 2010, the percent reductions in TCE range from 90 to 96%.

### **7.5.2 Soil Vapor Concentration Trends over Time**

A time trend graph for TCE in all of the individual soil vapor points is shown in Figure 7. From 1998 to 2007 average soil vapor TCE concentrations decreased approximately 40% to 65% for the five locations tested in both events (Table 14). From 2007 to 2010 average soil vapor TCE concentrations decreased approximately 77%, for the eleven locations where the 2007 concentrations were greater than  $8.0 \mu\text{g/m}^3$ . The reductions ranged from 65% to 95% for these locations. Excluding two anomalously low results from the 1998 data (SGOB27 and SGOB32), the remaining six soil vapor locations showed an average reduction of 93% from 1998 to 2010, with a range of 85% to 98%.

### **7.5.3 Sub-slab Vapor Concentration Trends over Time**

From 2001 to 2007 average sub-slab vapor TCE concentrations decreased approximately 40% to 65% for three of the five homes tested in both events (Figure 8). From 2001 to 2010 average sub-slab vapor TCE concentrations decreased approximately 70% for the three homes tested in both events (Table 15). Note that the 2010 results for 1235 Uinta are anomalously low (1% of the 2001 value) compared to the other three homes, probably due to insufficient time allowed for rebound of sub-slab concentrations after turning off the system a week prior to sampling. Three

of the homes with the highest concentration in 2007 (excluding 1235 Uinta) showed a 65% reduction in TCE concentration from 2007 to 2010.

#### **7.5.4 Indoor Air Concentration Trends over Time**

Although all homes were not tested in each study, it can be stated that the average reduction in indoor air TCE concentrations from 1998 (or 2001) to 2010 was approximately 75%. As noted in section 3.1, two of the homes sampled in either 1998 or 2001 (1264 and 1268 Uinta) did not grant access for sampling during either the 2007 or the present study and are not included in tabulations in this report. Note that of the eight homes tested in 1998, two had anomalously low results that are considered to be non-representative (1235 Uinta and 1329 Uinta) as described in Section 7.4.1. Unfortunately, none of the remaining six homes tested in 1998 were sampled in 2001, but it is expected that indoor air TCE concentrations would have shown little change over this time period due to lack of active groundwater remediation during this time period. The 1998 result for 1314 Ulster has no comparison value, because a radon system was operating in this home at the time of the 2007 sampling. The 1998 TCE results for 1235 Valentia and 1350 Ulster are considered to represent background values, as neither home had significant TCE in the sub-slab vapor at that time (Versar, 2001, Table 6-14) and therefore the percent reductions from 1998 are not calculated. The remaining three homes sampled in 1998 (1305 Uinta, 1330 Ulster, and 1353 Uinta) showed reductions of 96%, 64% and 63% respectively in indoor air TCE concentrations from 1998 to 2010 (Table 16). The only one of these homes sampled in 1998 that was sampled in another event besides 2010 (1305 Uinta) showed a reduction in indoor air TCE concentration of 94% from 1998 to 2007. From 2001 to 2007 average indoor air TCE concentrations decreased approximately 45% for the five homes tested in both events. From 2001 to 2010 average indoor air TCE concentrations decreased approximately 76% for the three homes tested in both events (excluding 1235 Uinta). Note that the 2010 results for 1235 Uinta are anomalously low (1% of the 2001 value) compared to the other three homes, probably due to insufficient time allowed for rebound of sub-slab concentrations after turning off the system a week prior to sampling. Two of the three homes with the highest concentration in 2007 (excluding 1235 Uinta) showed approximately a 75% reduction in TCE concentration from 2007 to 2010 (a range of 71 to 83%). The remaining three homes tested in 2010 and 2007 generally had indoor air results close to background or outdoor air levels in 2010 and thus were unable to show further reductions. As a result, these three homes showed lower apparent percentage reductions from 2007 to 2010. As noted above, given the somewhat limited data, it can be stated that the average reduction in indoor air TCE concentration from 1998 (or 2001) to 2010 was approximately 75%.

### **7.5.5 Comparison of Indoor Air to Sub-slab Vapor**

As expected, the reductions over time in indoor air and sub-slab vapor TCE concentration are very similar, with an average reduction of about 70 to 75% since 2001 (Figure 9).

### **7.5.6 Comparison of Indoor Air to Soil Vapor**

The reductions over time in indoor air and soil vapor TCE concentration are fairly similar, with an average reduction of about 75% in indoor air since 2001 and an average reduction of about 93% in soil gas since 1998 (Figure 9).

### **7.5.7 Comparison of Soil Vapor to Groundwater**

As expected, the reductions over time in groundwater and soil vapor TCE concentration are very similar, with an average reduction of about 90% in groundwater since 1998/2001 and an average reduction of about 93% in soil gas since 1998 (Figure 9).

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

The reductions over time in indoor air and groundwater TCE concentration are fairly similar, with an average reduction of about 75% in indoor air since 2001 and an average reduction of about 90% in groundwater since 2001 (Figures 9 and 10).

The above comparisons of trends and percent reductions in TCE over time suggest that sub-slab vapor and indoor air concentration reductions are lagging the reductions in groundwater and soil vapor, as would be expected theoretically due to the transport time of soil vapors from the water table, i.e., deep soil gas to the sub-slab and then indoor air. Within the next few years it is likely that the sub-slab vapor and indoor air TCE concentrations will also decrease the same amount as that observed in groundwater and soil gas (i.e., approximately 93% since 1998/2001), to the extent that indoor air concentrations are not due to background sources.

The continued action of residual permanganate and natural attenuation is likely to further reduce groundwater and soil gas TCE concentrations. Over time it is also likely that the sub-slab vapor and indoor air TCE concentrations will decrease the same amount as in groundwater and soil gas (i.e., more than the 93% observed since 1998/2001). A 93% reduction in indoor air TCE concentrations since 2001 would result in a maximum indoor air TCE concentration of 0.46  $\mu\text{g}/\text{m}^3$  due to vapor intrusion at the home with the highest indoor air TCE concentration (1238

Uinta) measured in 2001 (other than the mitigated home at 1235 Uinta). Greater percentage reductions due to continued decreases in groundwater concentrations would lead to even lower indoor air TCE concentrations.

## 8 CONCLUSIONS

TCE concentrations in all media (alluvial groundwater, soil gas, sub-slab vapor, and indoor air) showed substantial decreases (75-93%) over the 1998 to 2010 time frame, due to active groundwater remediation and natural attenuation processes. The decreases in the various media generally showed strong correlations. It is expected that continued decreases in TCE concentrations will occur in all media as a result of interactions in the aquifer with residual permanganate and natural attenuation processes and will achieve protection of human health in the near term.

The maximum indoor air TCE concentration in January 2010 was  $1.7 \mu\text{g}/\text{m}^3$  (at 1238 Uinta St. 1<sup>st</sup> floor); only two homes (1238 and 1282 Uinta) had TCE concentrations above the  $0.8 \mu\text{g}/\text{m}^3$  CDPHE policy action level. These samples were collected during the winter, and therefore most likely represent the maximum annual indoor air concentration. Based on the seasonal (bimonthly) sampling at these homes in 2000-2001 (Versar, 2003), winter indoor air concentrations are approximately 100% above the annual average concentration in a home (see table 5-1 of Versar, 2003). For long-term exposure estimates (30 years) the annual average is a more representative exposure concentration. The resulting calculated current annual average concentrations at the two homes with the highest TCE results in 2010 (1238 and 1282 Uinta) would be  $0.85 \mu\text{g}/\text{m}^3$  and  $0.55 \mu\text{g}/\text{m}^3$ , respectively. Given the observed direct correlation between alluvial groundwater and indoor air concentrations at the site, it would only require an additional 10% decrease ( $1 \mu\text{g}/\text{L}$  based on the current concentration) in groundwater TCE concentrations to produce annual average indoor air TCE concentrations that fall below  $0.8 \mu\text{g}/\text{m}^3$  for each tested home. The expected continued decrease in groundwater TCE concentrations should be able to achieve this result, and be protective of human health, without additional remedial measures.

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  $2.6 \times 10^{-5}$  to  $8.4 \times 10^{-4}$ , and  $9 \times 10^{-4}$  to  $1.1 \times 10^{-2}$ , which were within the 50<sup>th</sup> to 75<sup>th</sup> 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. This indicates that attenuation factors elsewhere over the off-site groundwater plume should be comparable, or even lower, as the depth to groundwater increases to the north and increasing thicknesses of fine-grained soils generally occur in the vadose zone and at the water table.

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## TABLES

## FIGURES

**On Attached Disc**

**APPENDIX A**

**Homeowner Questionnaires and Inspection Forms, Floor  
Plan Sketches, and Chemical Inventories**

**APPENDIX B**

**Soil Vapor Sample Collection Log**

**APPENDIX C**

**Sub-slab Vapor Sample Collection Log**

**APPENDIX D**

**2010 Laboratory Reports for Soil Vapor Samples**

**APPENDIX E**

**2010 Laboratory Reports for Sub-Slab Vapor and Indoor Air**