Investigation and Validation of Multiple Lines of Evidence to Assess Vapor Intrusion at Travis Air Force Base, CA

Final Report – Volume 1

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1 INTRODUCTION

Tetra Tech, Inc. (Tetra Tech) has been contracted by the United States Air Force (USAF), HSW/PKAH to conduct an investigation of multiple lines of evidence (MLE) used in assessing risk associated with the vapor intrusion (VI) pathway. To that end, research is being conducted at four Air Force installations where VI is suspected. The purpose of the investigations is to evaluate a variety of parameters related to VI in order to develop a better understanding of the processes that lead to a complete VI pathway, and ultimately, to develop tools for use by the Air Force in assessing VI at other installations.

Tetra Tech conducted a preliminary site visit to Travis Air Force Base (TAFB) in May 2008 to identify buildings considered likely to be subject to VI. Data provided by the TAFB 60 CES/CEVR Environmental Office were reviewed to identify suitable buildings located over shallow groundwater volatile organic compound (VOC) plumes. Criteria used to select candidate buildings were:

- Moderate size (i.e. less than 10,000 square feet)
- Slab-on-grade construction
- Closed interior space
- Limited occupancy (to avoid impacting mission operations)
- Location over a shallow groundwater VOC source
- Availability for conducting experiments

Based on these criteria, four candidate buildings were selected: Building 828, Building 836, Building 1001, and Building 1130. In May 2008, air samples were collected from these four building to verify the presence of VOCs. Similarly low concentrations of trichloroethene were detected in each of the buildings, suggesting the detected concentrations were representative of ambient air conditions at TAFB rather than resulting from VI. However, the concentrations of TCE detected in shallow groundwater plumes beneath these building suggested the potential for VI; therefore, it was determined that the follow up investigation at TAFB should focus on assessing the reasons for the absence of VI. Based on the preliminary sampling results and other considerations such as building size and construction, Building 828 was selected for the comprehensive investigation discussed in this report.

2 SITE BACKGROUND INFORMATION

2.1 Site background information

Building 828 is located in an industrial area on the southwest side of TAFB, California, on the northwest corner of Knapp Street and Boyles Street (Figure 2-1). Building 828 is bordered to the east by the runway complex, to the north by an aircraft hanger, to the west by Ragsdale Street, and to the southeast by an aircraft hanger that is currently under construction. Building 828 is the former Security Force Administration and Armory building, and is scheduled for demolition in 2009.

Figure 2-1
Location of Building 828, Travis Air Force Base.

The depth to groundwater in May 2007 was approximately 10 to 12 feet below ground surface (ft bgs) and groundwater appears to flow toward the south and southwest in the vicinity of Building 828 (60 CES/CEVR 2007, Figure 2-2). Shallow subsurface soils at TAFB are reported to consist primarily of silts and clays. Groundwater sampling at monitoring wells adjacent to Building 828 indicates that trichloroethene (TCE) is present at concentrations up to 1,700 micrograms per liter (µg/L), and a groundwater plume map indicates concentrations beneath Building 828 are projected to be on the order of 100 µg/L (60 CES/CEVR 2007). Table 2-1 summarizes the volatile organic compounds (VOCs) detected in groundwater wells adjacent to Building 828 and Figure 2-3 shows TCE groundwater plume contours.

Table 2-1
Summary of Groundwater Sampling Results from May 2007 (µg/L)

VOC	Maximum Concentration	Well
Benzene	0.19	MW539X37
Chloroform	0.19	MW540X37
Tetrachloroethene	38	MW540X37
TCE	1,700	MW524X37
1,2-Dichloroethane	0.56	MW539X37
cis-1,2-Dichloroethene	100	MW539X37
trans-1,2-Dichloroethene	29	MW524X37
1,1- Dichloroethene	1.1	MW524X37

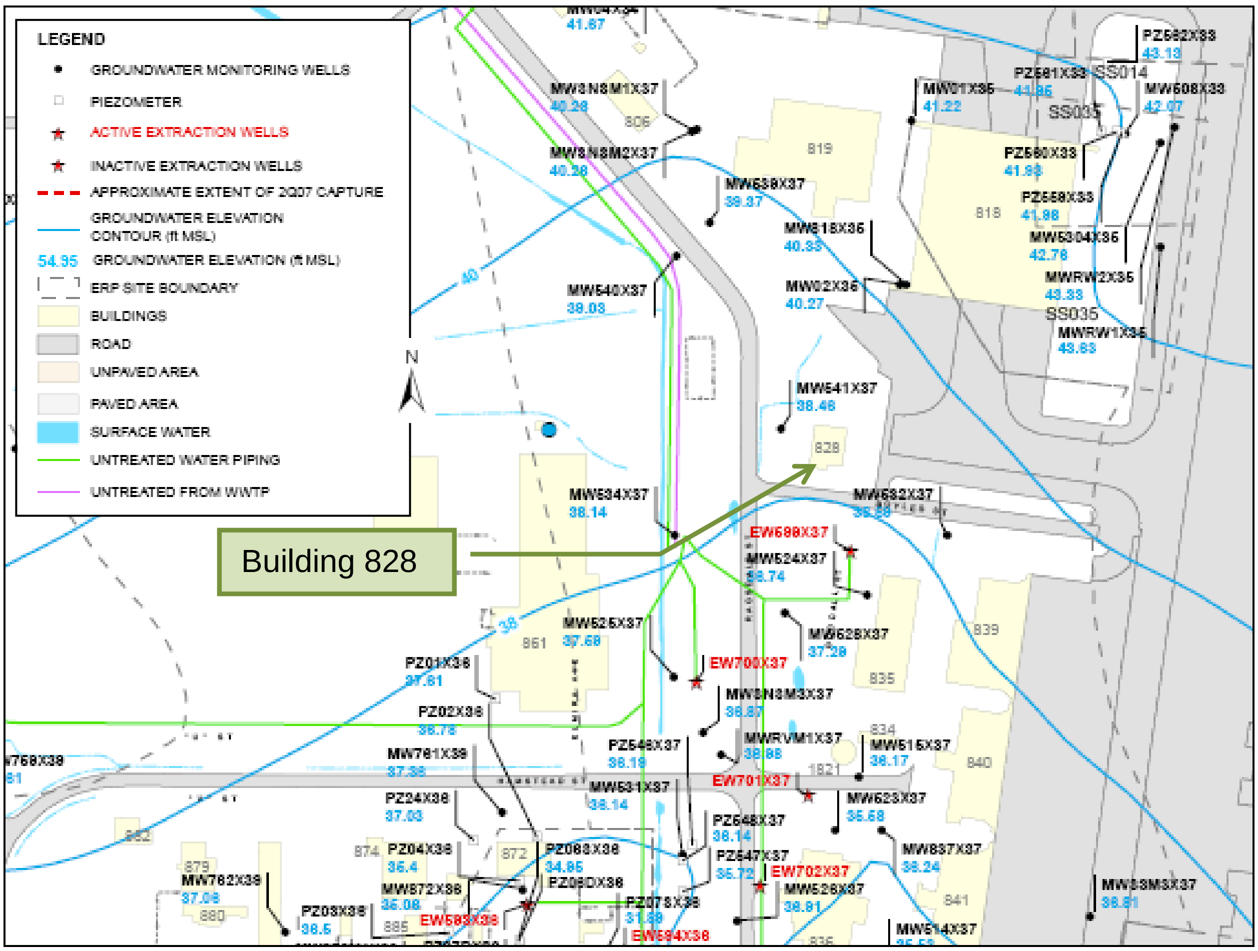


Figure 2-2
Groundwater elevation contours near Building 828. (Source: 60 CES/CEVR 2007).

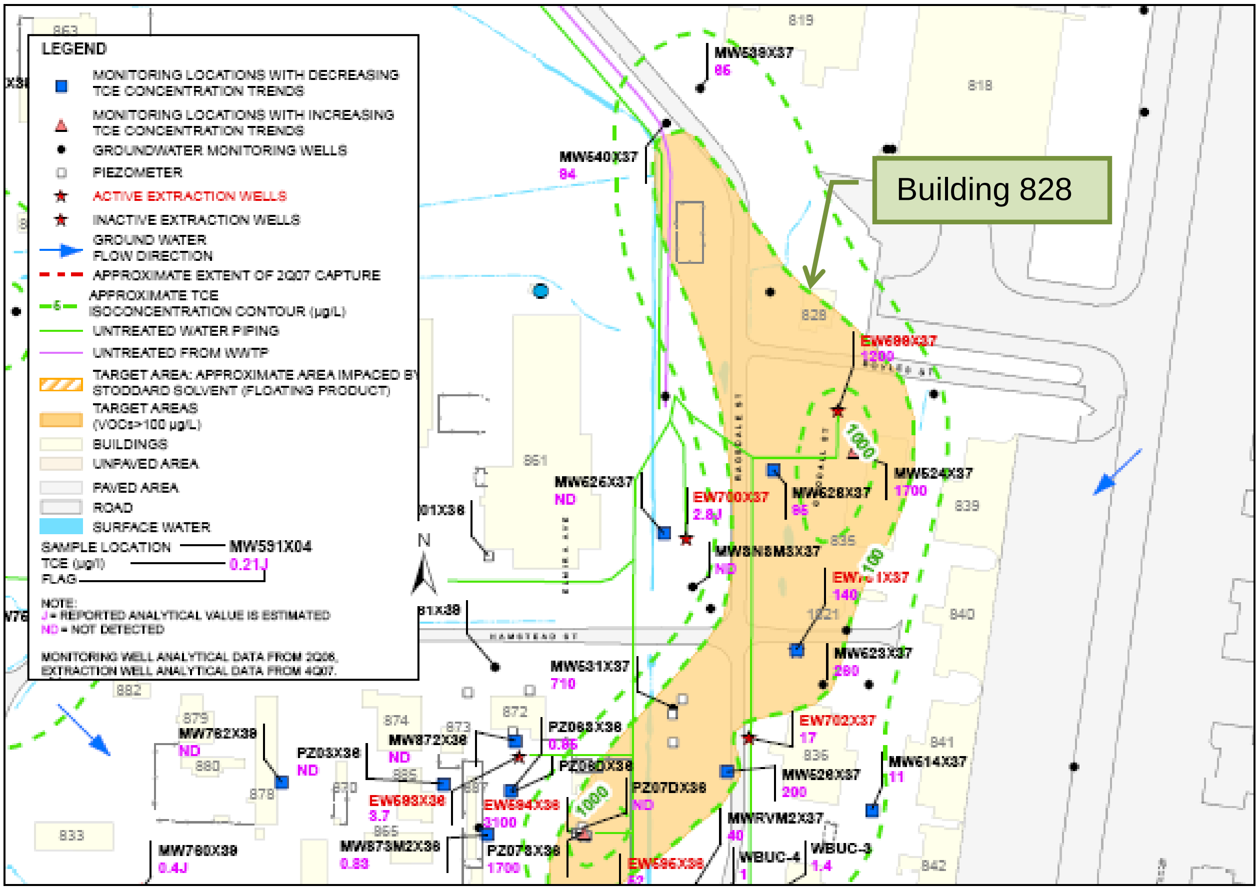


Figure 2-3
TCE Groundwater Plume Near Building 828. (Source: 60 CES/CEVR 2007).

2.2 Preliminary Field Sampling for Multiple Lines of Evidence Investigation

In May 2008, Tetra Tech conducted a reconnaissance visit to TAFB to identify buildings suitable for this investigation. Candidate buildings were selected based on the criteria listed in Section 1.0. Four buildings (828, 835, 1001, and 1130) were selected for preliminary indoor air sampling to assess the presence of VOCs in indoor air for this study. Indoor air sampling was conducted at each building using Summa Canisters equipped with 24-hour flow controllers. The indoor air samples were submitted to Air Toxics Ltd, located in Folsom, California, for analysis via U.S. Environmental Protection Agency (USEPA) method TO-15 with selected ion monitoring (SIM). The results of the preliminary indoor air sampling are summarized in Table 2-2. A fifth sample was collected in Building 554; however, this sample was collected to verify the efficacy of a soil vapor extraction system rather than to evaluate the building for this study.

Table 2-2
Preliminary Indoor Air Sampling Results (µg/m³)

	Building 1001	Building 828	Building 1130	Building 835
Trichloroethene	0.11	ND	0.29	0.028
Tetrachloroethene	0.03	0.016	0.02	0.042
1,1,1-Trichloroethane	0.052	0.049	0.054	0.071
1,2-Dichloroethane	0.047	0.039	0.039	0.15
Chloroform	0.061	0.056	0.043	0.089
Carbon Tetrachloride	0.4	0.4	0.41	ND

Notes:
µg/m³ – micrograms per cubic meter
ND – not detected

It can be seen in Table 2-2 that all of the buildings had very low VOC concentrations and that the concentrations are similar in each building. These observations suggests that the measured VOC concentrations reflect background ambient air concentrations at TAFB rather than VI. Similar results have been obtained from other recent indoor air sampling conducted by USEPA and CH2M Hill. However, if one uses the groundwater concentrations beneath these buildings as the source term, the Johnson and Ettinger (J&E) model (1991) predicts that VI should be occurring (discussed in Section 5). Therefore, the purpose of this investigation was to assess the reasons that VI appears not to be occurring.

2.2.1 Chemicals of Potential Concern Identified at the Site

Based on the groundwater concentrations summarized in Table 2-1, the primary chemical of potential concern (COPC) at Building 828 is TCE; however, additional chlorinated VOCs were assessed including tetrachloroethene (PCE), 1,2-dichloroethane (DCA), and dichloroethenes (DCEs).

Table 2-3
Chemicals of Potential Concern at Building 828

COPC	Level
Trichloroethene	Primary
Tetrachloroethene	Secondary
1,2-dichloroethane	Secondary
cis-1,2-dichloroethene	Secondary
trans-1,2-dichloroethene	Secondary
1,1-dichloroethene	Secondary

3 MULTIPLE LINES OF EVIDENCE FIELD INVESTIGATION

The MLE field investigation for TAFB was conducted during the period of 3 through 10 March 2009. A variety of parameters were measured during the field investigation to develop a comprehensive understanding of the processes occurring at the Site. The following sections detail the field activities.

3.1 Building description and indoor volume estimates

Building 828 is an approximately 1,370-square-foot, single story slab-on-grade structure. The building consists of an entry way, large closet, and six rooms: three offices, a communications room, a restroom, and the large weapons storage room (Figure 3-1). A concrete apron extends out from the north and east sides of the building. On the east (front) side the apron extends 24 feet, where it abuts the front asphalt parking lot. On the north side, the concrete apron extends approximately 27 feet, where it meets the side asphalt parking lot. This apron is covered by a 2,420-square-foot wood-constructed shed that is connected to the main building. The south and west sides of the building have no apron and are surrounded by a lawn.

During March 2009, detailed measurements were taken of each room in order to assess the indoor volume of Building 828. Indoor volume measurements are presented in Table 3-1. Each room contained various amounts of furniture and equipment that filled space. Therefore, the volumes presented in Table 3-1 are considered to have a margin of error of ±10 percent.

Table 3-1
Summary Table of Indoor Volumes for Building 828.

Room	Length (in)	Width (in)	Average Height (in)	Volume (ft^3)
Entry room	72	48	109	218
Office #1	180	132	109	1499
Office #2	180	158	109	1794
Office #3	123	126	109	978
Communications	199	126	109	1582
Weapon Storage (north end)	100	132	109	833
Weapon Storage (south end)	303	216	109	4128
Hall Closet (north end)	106	48	109	321
Hall Closet (south end)	96	81	109	491
Restroom	75	126	109	596
Total volume				**12,438**

The interior of building 828 has a drywall ceiling that slants slightly from the east side down to the west side (8 inches difference). The ceilings of the communications room, office #2, and office #3 are covered with acoustic tiles glued directly to the drywall that lower the ceiling approximately one half-inch. The same three rooms and the northern-most end of the hall closet have carpeted floors. All other floors in the building are covered with linoleum tiles. Figure 3-2 through Figure 3-5 are photographs of the outside and inside of Building 828.

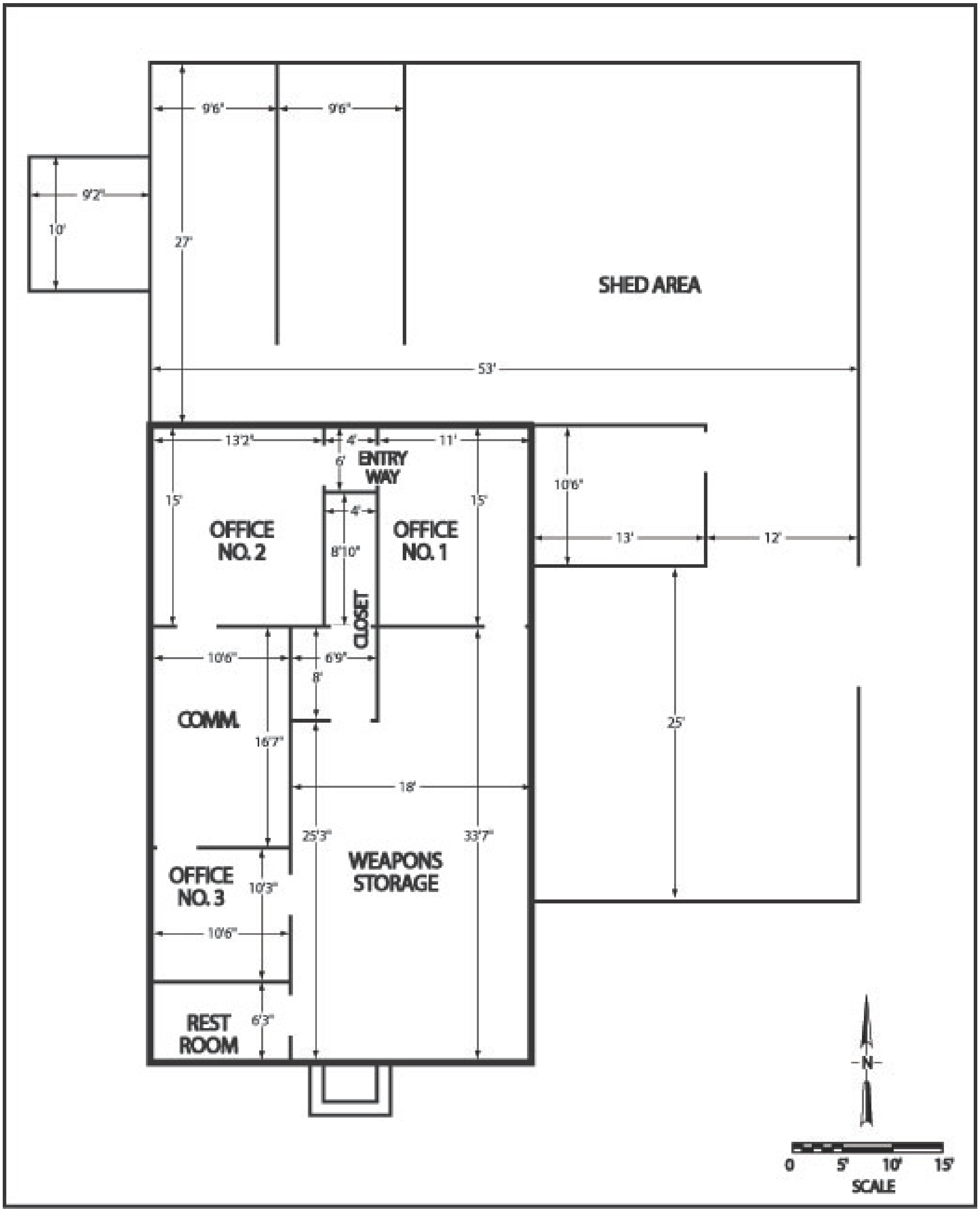


Figure 3-1
Floor plan of Building 828.

Figure 3-2
View of the southwest corner of Building 828 showing vapor probe locations Tt-SG-5 and Tt-SG-6.

Figure 3-3
View of the northwest corner of the shed area of Building 828 with SUMMA canister located at outdoor air sampling location 828-SM-ODN and the concrete apron of the side parking lot.

Figure 3-4
View from southeast corner of the large weapons storage room. Soil vapor probe location GSI-SS-1 is visible to the left of the desk in the foreground. Soil vapor probe location GSI-SS-2 is visible through the door in the background.

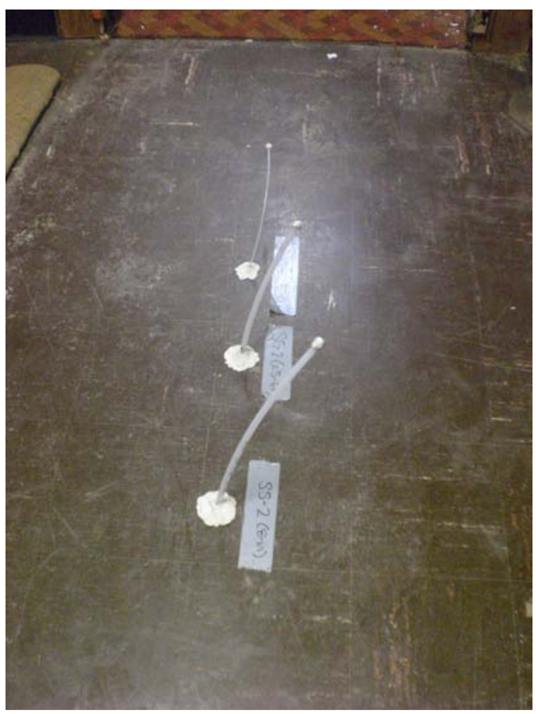


Figure 3-5
View of the closet showing the sub-slab (1/8" tubing) and 2.5 ft bgs pressure probe (1/4" tubing in middle) installed by GSI.

3.2 Sampling program design and execution

Field activities in support of the investigation were conducted from 3 March through 10 March 2009. Field activities included: (1) installation of one sub-slab soil vapor probe inside the building, one sub-slab vapor probe in the shed area beneath the concrete apron, three single soil vapor probes outside the building, and two sets of nested soil vapor probes (two depths each) outside the building; (2) collection of soil samples from selected soil borings; (3) collection of soil vapor samples; and (4) deployment of three SUMMA canisters. In addition, a known quantity of helium was released into the building and periodic indoor air samples were collected for off-site helium analysis in order to develop an estimate of the building air exchange rate. Sampling locations are shown on Figure 3-6. A summary of field activities including dates is provided in Table 3-2.

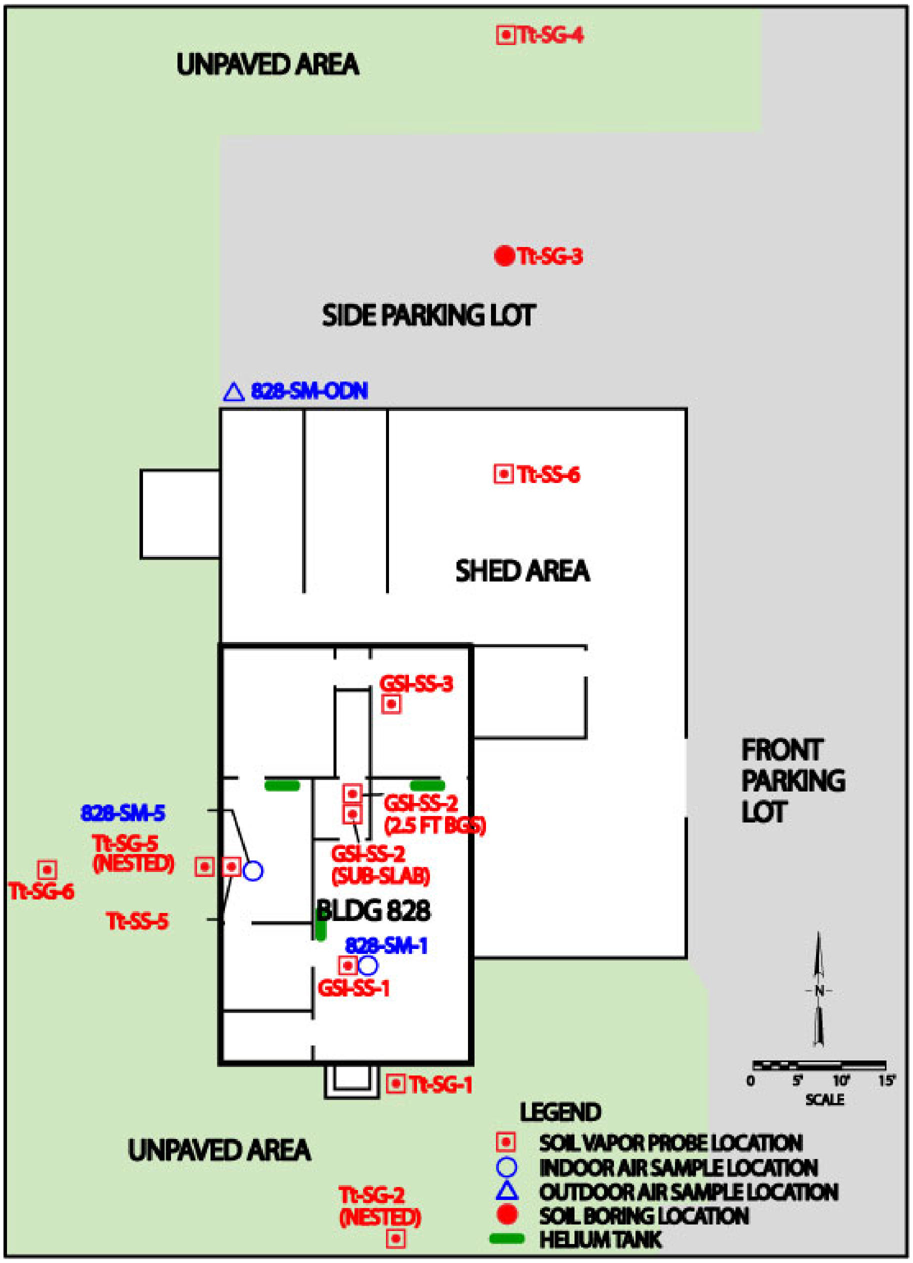


Figure 3-6
Sampling Locations.

Table 3-2
Summary of Field Activities

3 March 2009	Boring locations selected and marked for geophysical clearance. Building dimensions measured and recorded.
4 March 2009	Geophysical clearance of boring locations completed. Groundwater elevation measurements collected and recorded from existing groundwater monitoring and piezometer wells surrounding building 828. Borings Tt-SG-1, Tt-SG-2, Tt-SG-3, Tt-SG-4, Tt-SG-5, and Tt-SG-6 were drilled to 20 ft bgs. A rise in water level was observed in all borings immediately after puncturing the groundwater bearing unit (between 15 and 19 ft bgs). At the end of the day, water levels in all borings had risen to between 1.3 and 7.9 ft bgs. All borings were grouted after groundwater samples were collected. Three composite soil samples were collected from two borings that represent three slightly different lithologic units. The samples were sent offsite for physical parameters testing. Groundwater samples were collected from all six borings and sent offsite for analytical testing.
5 March 2009	Borings Tt-SG-1, Tt-SG-2, Tt-SG-3, Tt-SG-4, Tt-SG-5, and Tt-SG-6 were all redrilled at locations approximately 2 feet away from their previous locations. Borings Tt-SG-1, Tt-SG-4, and Tt-SG-6 were all drilled to 5.5 ft bgs. Boring Tt-SG-2 was advanced to 14.5 ft bgs. Boring Tt-SG-5 was advanced to 12.5 ft bgs. Drilling at Tt-SG-3 was stopped at 5 ft bgs after groundwater and meteoric water trapped beneath the asphalt inundated the boring. Soil vapor probes were installed in each of the five successful borings at 5 ft bgs. Nested wells were installed at Tt-SG-2 (5 feet and 14 ft bgs) and at Tt-SG-5 (5 feet and 12 ft bgs). One "outdoor" sub-slab soil vapor probe was installed at Tt-SS-6, located within the shed area. One indoor sub-slab soil vapor probe was installed at Tt-SS-5.
10 March 2009	SUMMA canisters deployed (two indoors and one outdoors) and collected. Air exchange rate investigation conducted via instantaneous release of approximately 375 ft^3 of helium into building and subsequent periodic sampling of indoor air. Soil vapor samples collected from soil vapor probes. Site cleaned up. All samples sent to offsite laboratories for analysis.

3.2.1 Soil Vapor Probe Installations

Prior to Tetra Tech's arrival at Building 828, GSI Environmental installed sub-slab soil vapor probes at three locations (GSI-SS-1, GSI-SS-2, and GS1-SS-3) directly beneath the slab inside Building 828 (Figure 3-5 and Figure 3-6). Due to their good condition, recent installation, and the location of these probes near Tetra Tech's proposed probe locations, Tetra Tech chose to utilize these probes for this investigation.

Tetra Tech installed one additional indoor sub-slab soil vapor probe (Tt-SS-5) directly beneath the slab inside Building 828 and one "outdoor" sub-slab soil vapor probe (Tt-SS-6) directly beneath the concrete apron inside the shed-covered area (Figure 3-6). Soil vapor probes consisting of 1-inch long gas permeable filters attached to 1/4-inch outer diameter Nylaflow tubing terminated by 3-way stopcock Luer valves were installed in holes drilled through the building slab/apron using a rotohammer drill with a 1.25-inch diameter drill bit and penetrating the sub-slab material just enough to accommodate the filters (approximately 1 to 2 inches). Prior to installation, the holes were cleaned with a damp towel to ensure a good seal. Sand to 1 inch above the filters and hydrated granular bentonite to grade completed the installations. Cement caps were not installed, because these probes are not permanent. The tubing extends approximately 12 inches above the surface from each location.

Two sets of nested soil vapor probes and three single shallow soil vapor probes were installed outside Building 828 at each location designated with an "SG" on Figure 3-6. The shallow probes were all set at 5 ft bgs and were designated Tt-SG1-5, Tt-SG2-5, Tt-SG4-5, Tt-SG5-5, and Tt-SG6-5 and the deep probes, which were set at 12 and 14-foot depths, were designated Tt-SG2-14 and Tt-SG5-12 (see soil vapor probe construction details provided in Appendix A).

The construction of the probes began on 4 March 2009. A direct-push track-mounted drilling rig was used to hydraulically drive 2.25-inch diameter rods containing 1.25-inch acetate sampling sleeves to a target depth of 20 ft bgs (the approximate maximum depth of groundwater in the area). Groundwater had been estimated to be approximately 15 to 20 ft bgs from previous groundwater monitoring reports; however, measurements taken in nearby groundwater wells on the day of drilling placed water level in the wells at 5.1 to 7.5 ft bgs. With this in mind, drilling at location Tt-SG-3 was done slowly and signs of groundwater were monitored. At 16.5 ft bgs groundwater was encountered and groundwater began rising up the bore hole. Within minutes of completing the boring to 20 ft bgs, the water level within the bore hole had risen to 8 ft bgs. Temporary PVC screen and casing was installed at Tt-SG-3 to allow groundwater to equalize. All other borings (Tt-SG-1, Tt-SG-2, and Tt-SG-4 through Tt-SG-6) were also drilled to 20 ft bgs. Groundwater was initially encountered between 15 and 19 ft bgs, but water level rose in all five borings once the groundwater bearing unit was penetrated. Temporary PVC was installed in all wells until groundwater samples could be collected. Soils were logged using continuous cores collected from each of the borings. Boring logs are provided in Appendix A.

Due to the groundwater inundation of the previously drilled borings, all six borings were re-drilled on 5 March 2009 at locations approximately 2 feet away from the original boring location in order to install vapor probes. Borings Tt-SG-1, Tt-SG-4, and Tt-SG-6 were all drilled to 5.5 ft bgs (a depth that would safely be well above groundwater). Boring Tt-SG-2 was advanced to 14.5 bgs (approximately 4.5 feet above the depth at which groundwater was initially encountered in the previous bore hole, but 7 below the final water level). Boring Tt-SG-5 was advanced to 12.5 ft bgs (approximately 2.5 feet above the depth at which groundwater was initially encountered in the previous bore hole, but 6 feet below the final water level). Drilling at Tt-SG-3 was stopped at 5 ft bgs after rainwater water trapped beneath the asphalt inundated the boring.

At each successful boring location, the deep probe filter was lowered to 6 inches above the total depth of the open boring. Sand was then poured into the boring so as to extend from 6 inches below to 6 inches above the filter. Then, granulated bentonite was poured into the boring and hydrated. For non-nested probes, this granulated bentonite was extended to the surface of the boring, was repeatedly hydrated during several lifts to ensure a proper seal, and was mounded around the probe tubing. For nested probes, the deeper probe sand pack was covered with one foot of hydrated granulatar bentonite, followed by bentonite chips to 5.5 ft bgs, topped with 6 inches of sand, the shallow soil vapor probe, 6 more inches of sand, and the final hydrated granular bentonite seal. Soil vapor probe tubing extended approximately 12 inches above the surface from each location.

3.2.2 Soil Vapor Probe, Soil, and Groundwater Sampling

On 10 March 2009, each soil vapor probe was sampled using a 60 milliliter (mL) syringe. In general, three system volumes were purged prior to filling a 500-ml Tedlar bag with 480mL of soil gas. Thus, approximately 12 mL from the sub-slab soil vapor probes and 72 mL from the shallow vapor probes were purged prior to sampling each location. In some cases, a vacuum developed during sampling due to the tight formation surrounding the probes. This was the case for both deep soil vapor probes. At both probes, a vacuum developed before purging could be completed; therefore, soil vapor samples were not collected. A vacuum was experienced when sampling some of the shallow soil vapor probes as well; however, after purging three system volumes, adequate sample volumes (> 100 mL) were obtained in each case, and a soil gas sample was collected. Purging and sampling with the same syringe at each location was accomplished via use of a 3-way stopcock Luer valve, minimizing the potential for outside contamination. Analytical results for soil gas samples are presented in Section 3.3.3 and discussed in Section 4.0.

While drilling at the six outside vapor probe locations, three visually differing soil types were identified (Appendix A). The first, occurring directly beneath the surface soil and extending to depths ranging from 11 to 19 ft bgs, consists of a firm to stiff, yellowish brown, moist clay. The second soil type, observed with gradational contacts with the clay at various depths in most borings, is a yellowish brown, fine to medium grained, clayey sand. Located only at the bottom of most borings, the third soil type consists of a yellowish brown, well graded, fine to medium sand with high clay content. In-tact soil samples were collected for physical parameters testing from borings Tt-SG-1 and Tt-SG-5. Two clay samples were collected from the 4-foot and 9-foot depths of both borings. The 4-foot and 9-foot samples consisted of two 6-inch sections of acetate sampling sleeve that were carefully cut and capped at either end, minimizing disturbance to the soil sample within. For each sample, one of the sleeves was obtained from boring Tt-SG-1 and the other from boring Tt-SG-5. The third soil sample was collected from Tt-SG-5 in the clayey sand horizon (the second most common sediment encountered). This sample consisted of only one 11-inch long sleeve. Results for soil samples are presented in Section 3.3.2 and discussed in Section 4.0.

Groundwater samples were collected from all six borings using polyurethane tubing fitted with a check valve that was lowered down the well through the PVC casing/screen. Analytical results for the groundwater samples are presented in Section 3.3.4 and discussed in Section 4.0.

3.2.3 Air Exchange Rate and Indoor and Outdoor Air Sampling

In order to estimate the indoor-outdoor air exchange rate, approximately 375 cubic feet (ft^3) of helium gas from three point sources were released into the building on 10 March 2009. The sources were three 125 ft^3 cylinders, which were placed in the weapons storage and communications rooms of Building 828 (Figure 3-6). The building was kept closed except during brief moments when field personnel entered or exited the building through the door between the entry room and the shed area. Therefore, helium was not released into the shed area, and the air exchange rate calculations were based on the interior volume of the building with the shed area excluded. The tank valves were fully opened simultaneously by the field crew, allowing the tanks to empty into the building. Each cylinder emptied in approximately 1 minute. Indoor air samples integrated throughout each room of the building were subsequently collected from chest-height into Tedlar bags using a 60-ml syringe 15, 30, and 60 minutes after release, and again at 2, 4, 6, and 8 hours after release. Additional samples were collected from 1 foot below the ceiling and immediately above the ground surface at 15, 30, and 120 minutes after release to evaluate potential vertical stratification of the helium gas within the building. Analytical results for the helium sampling are presented in Section 3.3.5 and discussed in Section 4.0.

On 10 March 2009, two SUMMA canisters were deployed inside the building (828-SM-1 and 828-SM-5) and one was deployed outside on the north side of the building (828-SM-ODN)

(Figure 3-6). The indoor canisters were placed near sub-slab soil gas sampling points and at elevated locations where possible (e.g., on tables), in order to obtain samples more representative of the breathing zone. Canister 828-SM-1 was closed after sampling for a 6-hour and 50-minute period as it was filling faster than intended, and canisters 828-SM-5 and 828-SM-ODN were closed after sampling for 8 hours. Analytical results are presented in Section 3.3.5 and discussed in Section 4.0.

3.2.4 Variances

The work plan proposed drilling through the sub-slab of building 828 to install four interior sub-slab soil vapor probes. After the submittal of the work plan, Tetra Tech became aware of three interior sub-slab soil vapor probes that had been recently installed inside Building 828 by GSI Environmental. Rather than duplicate efforts, the three GSI vapor probes were used and only one additional probe was installed. Construction information for the GSI probes is provided in Appendix A.

The work plan proposed drilling six outdoor borings and installing a total of twelve soil vapor probes (one at 5 ft bgs and one at just above the groundwater in each boring); however, only five 5-foot probes and two deep probes were installed. During the course of the fieldwork, six borings were advanced as planned, but after encountering groundwater at depths ranging from 15 to 19 ft bgs, water in each bore hole rose to between 1.3 and 7.9 ft bgs. Four of the borings were redrilled to 5.5 ft bgs and soil vapor probes were successfully installed at 5 ft bgs in three of the four borings. One of the borings (Tt-SG-3, located within the north asphalt parking lot) immediately filled with rainwater trapped under the asphalt and so no probes could be installed. This water inundation also made it impossible to install the sub-slab soil vapor probe proposed for this location. At two of the proposed outdoor probe locations (Tt-SG-5 and Tt-SG-2), borings were advanced to deeper depths (12.5 and 14.5 ft bgs, respectively) in an attempt to approach, but not reach, the groundwater previously encountered at these locations. Soil vapor probes were installed at 5 ft bgs and at the bottom of each of these bore holes.

In the work plan, soil gas samples were proposed to be collected from each indoor and outdoor probe installed; however, some probes were not sampled. During the course of the field work, all indoor sub-slab probes were sampled, but a tight formation surrounding some of the outdoor probes created a strong vacuum that made sample collection impossible at the two deep probe locations (Tt-SG-2 at 14 feet and Tt-SG-5 at 12 feet). Samples were collected at all five 5-foot probes, but due to vacuum, some samples were less than the proposed 480 mL volume.

As proposed in the work plan, three SUMMA canisters were deployed at the site (two interior and one exterior). The sampling duration for each canister was set for 8 hours with a start time of 0920 and an anticipated end time of 1720; however, a check of the canisters at 1530 revealed that one of the indoor canisters (sample 828-SM-1) was filling too fast and was nearly full. Therefore, canister 828-SM-1 filled for 6 hours and 50 minutes instead of the full 8 hours.

3.3 Analytical Data results

3.3.1 Meteorology During Sampling Event

The Helium for the air exchange rate investigation was released at 0945 on 10 March 2009 and sampling for Helium in indoor air was performed from 1000 to 1745 on 10 March 2009. The

SUMMA canisters were deployed at 0920 on 10 March 2009 and sampling was stopped at 1610, 1720, and 1725 on the same day. Soil gas sampling was conducted between 1045 and 1345 on 10 March 2009. Figure 3-7 illustrates local meteorological data from 0000 to 2400 on 10 March 2009. The data were gathered from weather station KSUU located at the TAFB airport, approximately 1 mile east of Building 828 (Weather Underground 2009).

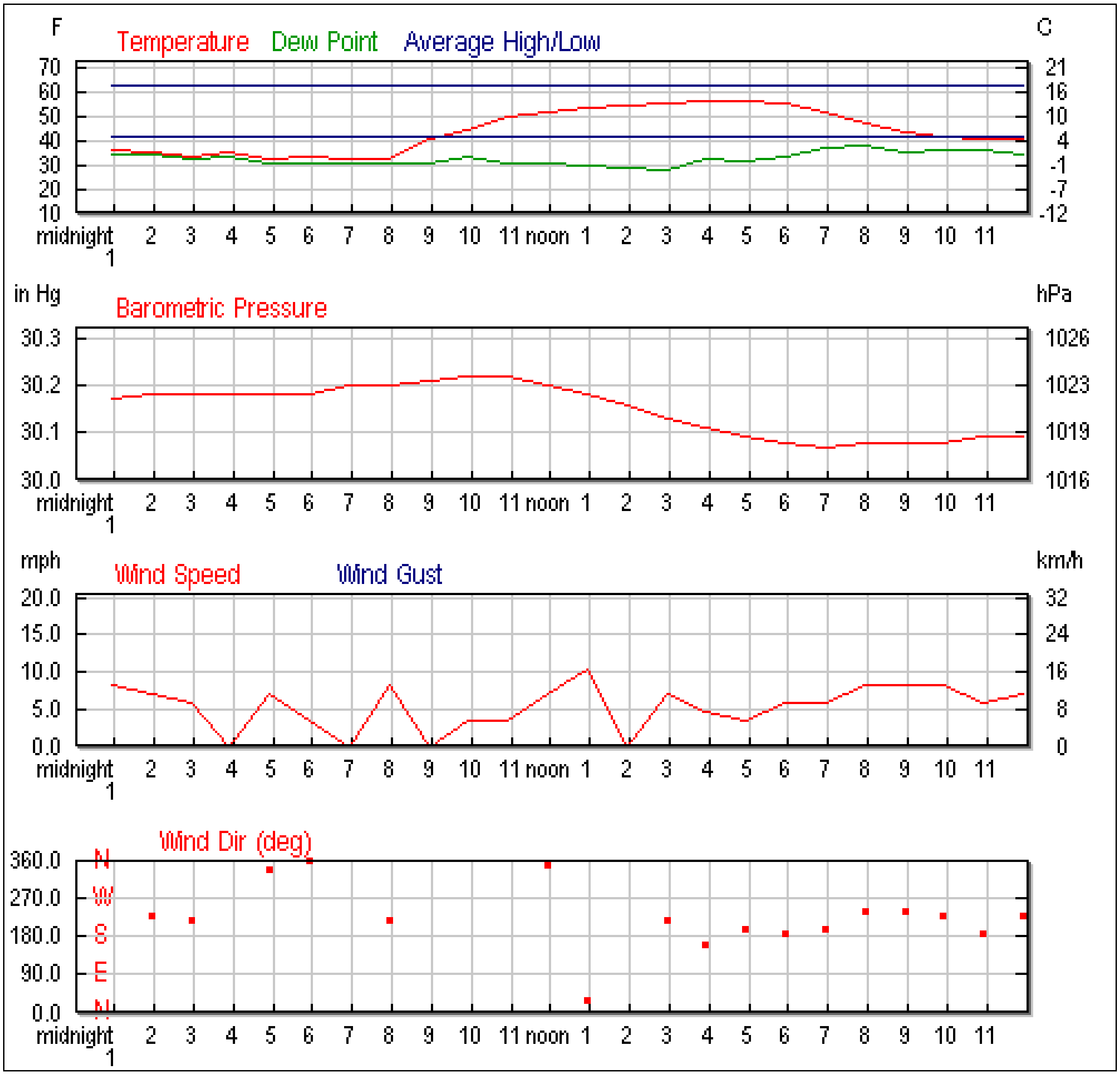


Figure 3-7
Meteorological data for 10 March 2009, collected from weather station KSUU, located approximately 1 mile east of Building 828 (Source: Weather Underground 2009).

3.3.2 Soil Physical Properties

Off-site laboratory analysis for soil physical properties was performed by Keantan Laboratories, located in Diamond Bar, California. Soil samples Tt-SG1/5-4, Tt-SG1/5-9, and Tt-SG5-19 were analyzed for moisture content, dry density, total organic carbon (TOC), total porosity, effective permeability, and air conductivity. Analytical test results are presented in Table 3-3 and discussed in Section 4.0. Boring logs describing soil lithology at sample depth are provided in Appendix A. The laboratory report including chain-of-custody (COC) records for these analyses is provided as Appendix B.

Table 3-3
Soil Physical Parameters at USAFSAM, Building 828, Travis AFB, California

Sample ID	Collection Date	USCS Classification	Moisture Content (%)	Dry Density (pcf)	TOC (%)	Total Porosity (%)	Effective Permeability (millidarcy)	Air Conductivity (cm/second)
Tt-SG1/5-4	05-Mar-09	CL-ML	21.44	91.80	0.40	0.35	0.350	2.5E+08
Tt-SG1/5-9	05-Mar-09	CL-ML	14.29	99.56	0.03	0.40	0.263	1.8E+08
Tt-SG5-19	05-Mar-09	CL-ML	24.83	77.40	0.08	0.53	5.18	3.7E+07

Definitions:
cm-centimeter
pcf-pounds per cubic foot
SP-poorly graded sand
SW-well graded sand
TOC-total organic carbon
USCS-Universal Soil Classification System
Note:
1-Samples contain shell fragments.

3.3.3 Soil Vapor Sample Results

Off-site laboratory analysis for soil gas samples was performed by H&P Laboratories, located in Carlsbad, California. Indoor sub-slab samples 828-SS-1, 828-SS-2, 828-SS-2-2.5, 828-SS-3, and 828-SS-5, shed area sub-slab samples 828-SS-6 and 828-SS-Dup (associated with sampling location 828-SS-6), and outdoor samples 828-SG-1-5, 828-SG-2-5, 828-SG-4-5, 828-SG-5-5, and 828-SG-6-5 were analyzed for VOCs using modified EPA method TO15. Analytical results are presented in Table 3-4 and are discussed in Section 4.0. The laboratory report including COC records is provided as Appendix C.

Table 3-4
VOCs in Soil Gas (µg/m3) at USAFSAM, Building 828, Travis AFB, California

Sample Location	Tt-SG-1	Tt-SG-2	Tt-SG-4	Tt-SG-5	Tt-SG-6	GSI-SS-1	GSI-SS-2
Sample ID	828-SG-1-5	828-SG-2-5	828-SG-4-5	828-SG-5-5	828-SG-6-5	828-SS-1	828-SS-2
Sample Depth (feet bgs)	5	5	5	5	5	SS	SS
Collection Date	3/10/2009	3/10/2009	3/10/2009	3/10/2009	3/10/2009	3/10/2009	3/10/2009
Volume, ml	72	72	72	72	72	12	12
PCE	ND	ND	6.5	5.8	5.6	ND	ND
TCE	ND	11	ND	ND	ND	ND	ND
cis-1,2-DCE	ND	ND	ND	ND	ND	ND	ND
trans-1,2-DCE	ND	ND	ND	ND	ND	ND	ND
Vinyl chloride	ND	ND	ND	ND	ND	ND	ND
1,1,1-TCA	ND	ND	ND	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND
1,1,2-TCA	ND	ND	ND	ND	ND	ND	ND
1,1,2-Trichlorotrifluoroethane	61	ND	ND	ND	26	ND	ND
1,1-DCA	ND	ND	ND	ND	ND	ND	ND
1,1-DCE	ND	ND	ND	ND	ND	ND	ND
1,2-DCA	ND	ND	ND	ND	ND	ND	ND
1,2,4-Trimethylbezene	ND	5.4	ND	6.0	5.8	ND	ND
2-Butanone	ND	ND	5.2	ND	ND	ND	ND
Acetone	290	ND	450	530	60	26	32
Benzene	17	36	130	79	14	ND	ND
Carbon disulfide	31	120	75	240	14	18	24
Carbon tetrachloride	ND	ND	ND	ND	ND	ND	ND
Chloroform	ND	41	ND	41	ND	ND	ND
Cyclohexane	ND	58	150	170	28	ND	22
Ethylbenzene	10	19	16	30	17	ND	ND
m,p-Xylenes	47	54	50	79	45	9.8	9.7
n-Heptane	ND	59	410	360	15	ND	ND
n-Hexane	32	190	470	470	31	ND	ND
o-Xylene	10	15	13	19	13	ND	ND
Propene	130	3,600 E	2,200 E	6,000 E	69	ND	ND
Toluene	140	170	260	490	90	16	15

Table 3-4
VOCs in Soil Gas (µg/m3) at USAFSAM, Building 828, Travis AFB, California

Sample Location	**GSI-SS-2**	**GSI-SS-3**	**Tt-SS-5**	**Tt-SS-6**	**Tt-SS-6**
Sample ID	**828-SS-2-2.5**	**828-SS-3**	**828-SS-5**	**828-SS-6**	**828-SS-DUP**
Sample Depth (feet bgs)	**2.5**	**SS**	**SS**	**SS**	**SS**
Collection Date	3/10/2009	3/10/2009	3/10/2009	3/10/2009	3/10/2009
Volume, ml	36	12	12	72	72
PCE	ND	ND	ND	ND	ND
TCE	ND	ND	ND	ND	ND
cis-1,2-DCE	ND	ND	ND	ND	ND
trans-1,2-DCE	ND	ND	ND	ND	ND
Vinyl chloride	ND	ND	ND	ND	ND
1,1,1-TCA	ND	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND
1,1,2-TCA	ND	ND	ND	ND	ND
1,1,2-Trichlorotrifluoroethane	ND	25	ND	ND	ND
1,1-DCA	ND	ND	ND	ND	ND
1,1-DCE	ND	ND	ND	ND	ND
1,2-DCA	ND	ND	ND	ND	ND
1,2,4-Trimethylbezene	ND	ND	ND	ND	ND
2-Butanone	ND	ND	ND	ND	ND
Acetone	33	30	46	280	ND
Benzene	ND	ND	ND	ND	ND
Carbon disulfide	21	18	22	ND	ND
Carbon tetrachloride	ND	ND	ND	ND	ND
Chloroform	ND	ND	ND	ND	ND
Cyclohexane	40	ND	ND	ND	ND
Ethylbenzene	ND	ND	ND	130	110
m,p-Xylenes	9.0	8.3	19	260	240
n-Heptane	ND	ND	ND	ND	ND
n-Hexane	ND	ND	ND	ND	ND
o-Xylene	ND	ND	ND	65	52
Propene	ND	ND	83	ND	ND
Toluene	15	13	47	2,200	1,800

Data Validity Qualifier:
E - The concentration indicated for this analyte is an estimated value above the calibration range of the instrument.
This value is considered an estimate.
Definitions:
bgs - below ground surface
DCA - dichloroethane
DCE – dichloroethene
DUP - duplicate sample
EPA - Environmental Protection Agency
µg/m^3 - micrograms per cubic meter
ml - milliliter
ND - not detected
PCE - tetrachloroethene
SS - sub-slab
TCA - trichloroethane
TCE – trichloroethene
Notes:
Samples analyzed using EPA method TO-15
All results in µg/m^3

3.3.4 Groundwater Sample Results

Off-site laboratory analysis for groundwater samples was performed by American Environmental Testing Laboratory, Inc., located in Burbank, California. Groundwater samples Tt-SG-1 through Tt-SG-6 were analyzed by USEPA method SW8260. Duplicate sample DUP1 is associated with sample location Tt-SG-4. Analytical results are presented in Table 3-5 and are discussed in Section 4.0. The laboratory report including COC records is provided as Appendix D.

Table 3-5
VOCs in Groundwater at USAFSAM, Building 828, Travis AFB, California

Sample ID	TT-SG-1	TT-SG-2	TT-SG-3	TT-SG-4	DUP1	TT-SG-5	TT-SG-6
Collection Date	**3/4/2009**	**3/4/2009**	**3/4/2009**	**3/4/2009**	**3/4/2009**	**3/4/2009**	**3/4/2009**
PCE	ND	ND	ND	ND	ND	ND	ND
TCE	27.4	23.4	2.83	1.85	2.39	9.01	19.4
cis-1,2-DCE	8.74	6.73	0.770 J	ND	ND	2.87	7.55
trans-1,2-DCE	ND	ND	ND	ND	ND	ND	ND
Vinyl chloride	ND	ND	ND	ND	ND	ND	ND
1,1,1-TCA	ND	ND	ND	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND
1,1,2-TCA	ND	ND	ND	ND	ND	ND	ND
1,1,2-Trichlorotrifluoroethane	ND	ND	ND	ND	ND	ND	ND
1,1-DCA	ND	ND	ND	ND	ND	ND	ND
1,1-DCE	ND	ND	ND	ND	ND	ND	ND
1,2-DCA	ND	ND	ND	ND	ND	ND	ND
1,2,4-Trimethylbezene	ND	ND	ND	ND	ND	ND	ND
2-Butanone	ND	ND	ND	ND	ND	ND	ND
Acetone	ND	ND	ND	ND	ND	ND	ND
Benzene	ND	ND	ND	ND	ND	ND	ND
Carbon disulfide	ND	ND	ND	ND	ND	ND	ND
Carbon tetrachloride	ND	ND	ND	ND	ND	ND	ND
Chloroform	ND	ND	ND	ND	ND	ND	ND
Cyclohexane	ND	ND	ND	ND	ND	ND	ND
Ethylbenzene	ND	ND	ND	ND	ND	ND	ND
m,p-Xylenes	ND	ND	ND	ND	ND	ND	ND
n-Heptane	ND	ND	ND	ND	ND	ND	ND
n-Hexane	ND	ND	ND	ND	ND	ND	ND
o-Xylene	ND	ND	ND	ND	ND	ND	ND
Propene	ND	ND	ND	ND	ND	ND	ND
Toluene	ND	ND	ND	ND	ND	ND	ND

Data Validity Qualifier:
J - The analyte was positively identified and the result is usable; however, the analyte concentration is an estimated value.

Definitions:
DCA - dichloroethane
DCE - dichloroethene
DUP - duplicate sample
µg/L - micrograms per Liter
ND - not detected
PCE - tetrachloroethene
TCA - trichloroethane
TCE - trichloroethene

Notes:
Samples analyzed using EPA method SW8260B
All results in µg/L

3.3.5 Indoor and Outdoor Air Data

Off-site laboratory analysis for indoor and outdoor air samples was performed by Air Toxics Ltd., located in Folsom, California. Samples 828-SM-1, 828-SM-5, and 828-SM-ODN, collected with SUMMA canisters, were analyzed using EPA method TO-15 in selected ion monitoring (SIM) mode. Analytical data results for TO-15 are presented in Table 3-6. Laboratory data reports including COC records are provided in Appendix E.

Table 3-6
VOCs in Air (µg/m^3) at USAFSAM, Building 828, Travis AFB, California

Sample ID		828-SM-1		828-SM-5		828-SM-ODN	
Collection Data	**RL**	**10-Mar-2009**		**10-Mar-2009**		**10-Mar-2009**	
PCE	0.020	0.052		0.045		0.026	J
TCE	0.016	3.9		2.7		0.022	J
cis-1,2-DCE	0.079	1.6		1.0		<0.12	
trans-1,2-DCE	0.40	0.22	J	0.16	J	<0.63	
Vinyl chloride	0.026	<0.040		<0.048		<0.040	
1,1,1-TCA	0.110	0.047	J	0.056	J	0.048	J
1,1,2,2-Tetrachloroethane	0.14	<0.21		<0.26		<0.22	
1,1,2-TCA	0.11	<0.17		<0.20		<0.17	
1,1-DCA	0.081	<0.12		<0.15		<0.13	
1,1-DCE	0.040	<0.061		<0.074		<0.063	
1,2-DCA	0.081	0.048	J	0.054	J	0.050	J
Benzene	0.16	0.44		0.42		0.32	
Carbon tetrachloride	0.12	0.45		0.46		0.46	
Chloroform	0.098	0.072	J	0.069	J	0.056	J
Ethylbenzene	0.087	0.24		0.32		0.055	J
m,p-Xylenes	0.17	0.62		0.82		0.11	J
o-Xylene	0.087	0.14		0.18		0.042	J
Toluene	0.075	1.3		1.7		0.33	

Data Validity Qualifier:
J-The analyte was positively identified and the result is usable; however, the analyte concentration is an estimated value.
Definitions:
DCA-dichloroethane
DCE-dichloroethene
EPA-Environmental Protection Agency
µg/m^3-micrograms per cubic meter
ND-not detected
PCE-tetrachloroethene
RL-reporting limit
TCE-trichloroethene
VOC-volatile organic compound
Notes:
Samples analyzed using EPA method TO-15 SIM
All results in µg/m^3

Off-site laboratory analysis for indoor air in support of the air exchange rate investigation was performed by Air Toxics Ltd. All samples were analyzed for Helium in air by modified ASTM Method D-1946. Analytical data results are presented in Table 3-7 and are discussed in Section 4.0. The laboratory report including COC records is provided in Appendix E.

Table 3-7
Helium Concentrations in Indoor Air (percent) Air Exchange Measurement at USAFSAM, Building 828, Travis AFB, California

Sample ID	Collection Date	Collection Time	Time After He Release (min)	RL	Result
He15L	10-Mar-09	1002	15	0.050	0.54
He15M	10-Mar-09	1000	15	0.050	0.97
He15H	10-Mar-09	1004	15	0.050	1.5
He30L	10-Mar-09	1017	30	0.050	0.13
He30M	10-Mar-09	1015	30	0.050	0.78
He30H	10-Mar-09	1019	30	0.050	1.1
He60	10-Mar-09	1045	60	0.050	0.80
He120L	10-Mar-09	1147	120	0.050	0.32
He120M	10-Mar-09	1145	120	0.050	0.22
He120H	10-Mar-09	1149	120	0.050	0.20
He240	10-Mar-09	1345	240	0.050	0.11
He360	10-Mar-09	1545	360	0.050	<0.050
He480	10-Mar-09	1745	480	0.050	<0.050

Definitions:
ASTM-American Society for Testing and Materials
RL-reporting limit
Note:
Samples analyzed using ASTM method D-1946
All results in percent

3.3.6 QA/QC Considerations

All laboratory analyses and data validation were performed in accordance with Appendix F. Several data quality discrepancies were encountered.

The indoor SUMMA canister 828-SM-1 filled faster than anticipated and had to be closed prematurely. Therefore, the sample collected was not integrated over an 8-hour period.

This discrepancy is considered minor and does not significantly impact the data quality or interpretations presented in this report.

4 ANALYSIS OF DATA

4.1 Air Exchange Rate (AER) Analysis

Air exchange rates were experimentally determined by instantaneously releasing a known mass of helium into Building 828, and periodically collecting samples of air containing helium in the building at times subsequent to the release. The theoretical basis for each of two methods used is presented in Appendix I. The results are presented graphically in Figure 4-1 for each of the two methods. The predicted air exchange rate ranged from 13.2/day (Method 2) to 16.9/day for Method 1. Method 2, as described in Appendix I, does not rely on knowing the initial mass of helium released, while Method 1 does.

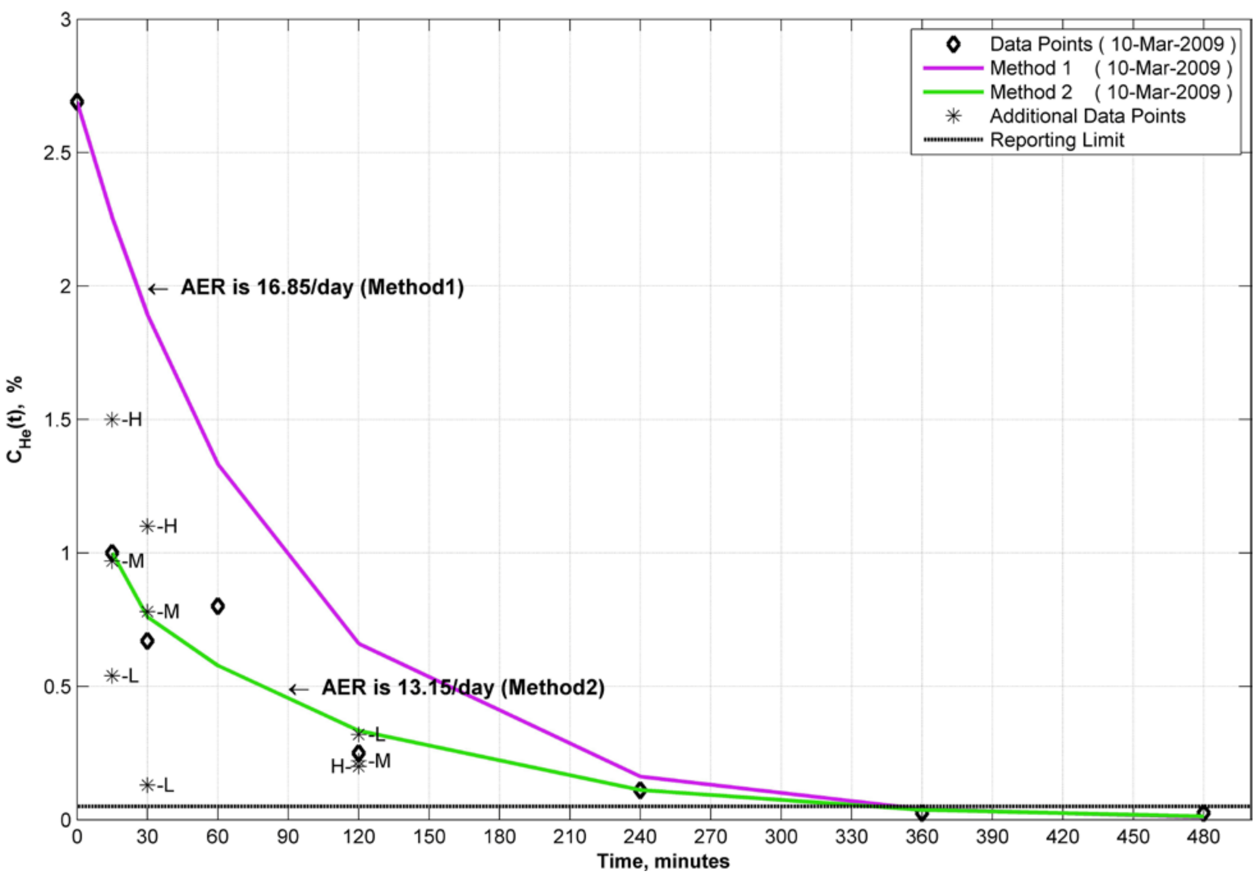


Figure 4-1
Analysis of Air Exchange Rate (AER) Using Instantaneously Released He. (Method 1 and 2)

For the tests, the helium was released from three cylinders spaced in the main structure of the building, as shown previously in Figure 3-6. Since this structure was isolated from the shelter extension, the volume used for the AER calculations was the volume of the main building, and is shown in Table 4-1. Three canisters of He were released, and based on the characteristics of the canister, it was estimated that 1.54 kg of He was released. This estimate was used to calculate the initial He concentration for Method #1.

Table 4-1
Travis Building 828 Dimensions (Main Structure)

Room	Length (in)	Width (in)	Average Height (in)	Volume (ft^3)
Entry room	72	48	109	218
Office #1	180	132	109	1499
Office #2	180	158	109	1794
Office #3	123	126	109	978
Communications	199	126	109	1582
Weapon Storage (north end)	100	132	109	833
Weapon Storage (south end)	303	216	109	4128
Hall Closet (north end)	106	48	109	321
Hall Closet (south end)	96	81	109	491
Restroom	75	126	109	596
Total volume				**12,438**

Notes:
Building has a slanted roof that angles from east to west with a total height difference of 8 inches.
Building has dry wall ceilings with acoustical tiles glued directly to dry wall in 3 rooms (Office #2, Office #3, Communications)

Helium samples were collected at multiple heights at 15 minutes, 30 minutes, and 120 minutes following its release. Three samples were collected at each of those times at different vertical heights (labeled low (L), medium (M), and high (H) in Figure 4-1). The samples labeled H were collected at about 7 feet above the floor, the samples labeled M were collected at about 5 feet above the floor, and the samples labeled L were collected about 3 feet above the floor. For the AER analysis an average of the three samples was used as representative of the He concentration in the building at that time. It is clear from the data points in Figure 4-1 that the helium was stratified for at least the first 30 minutes. By 120 minutes, the helium was nearly well mixed throughout the building.

4.2 Discussion of Soil Gas Data, Groundwater Data, Indoor Air Data, and Outdoor Air Data Collected During the Field Investigation

This discussion focuses on TCE and cis-1,2-DCE, and on benzene, toluene, ethylbenzene, and xylenes (BTEX). Compared to previous investigations at Cape Canaveral Air Force Station and Kelley Air Force Base, significant concentrations of BTEX have been detected at Travis AFB. TCE and cis-1,2-DCE have been found at all bases investigated.

A summary of the data is shown in Table 4-2 (TCE and cis-1,2-DCE), Table 4-3 (benzene and toluene) and in Table 4-4 (ethylbenzene and xylenes). Each data point where a sample was collected is identified by its sample identification, location, and depth bgs, as applicable. Of the data sets in the three tables, only TCE and cis-1,2-DCE were detectable in both the groundwater and in indoor air, but not in soil gas (with one exception: 11 $\mu g/m^3$ of TCE were detected at Tt-SG-2). In contrast, BTEX was detected in the soil gas, in indoor air, and in outdoor air, but not in groundwater.

The soil gas samples shown in the three tables were collected directly beneath the slab (SS) and at depths of 2.5 to 5.0 bgs. The depth to groundwater ranged from 15 to 19 bgs. The sampling depths for groundwater indicated on Tables 4-2 through 4-4 reflect the depth at which groundwater was first encountered in the specific boreholes, rather than the depth to which the groundwater rose. As the soil gas probes were set at depths of 2.5 to 5 feet bgs, the vertical distance between the soil gas probes and groundwater was over 10 feet.

Table 4-2
TCE and cis-1,2-DCE Data Collected at Travis AFB (all concentrations μg/m^3)[1]

Sample ID/Location (feet bgs)	Soil Gas	Groundwater	Indoor Air	Outdoor Air
828-SG-1-5/Tt-SG-1 (5)	<10/<10	-	-	-
828-SG-2-5/Tt-SG-2 (5)	11/<5	-	-	-
828-SG-4/Tt-SG-4 (5)	<5/<5	-	-	-
828-SG-5-5/Tt-SG-5 (5)	<5/<5	-	-	-
828-SG-6-5/Tt-SG-6 (5)	<5/<5	-	-	-
828-SS-1/GSI-SS-1 (SS)	<5/<5	-	-	-
828-SS-2/GSI-SS-2 (SS)	<5/<5	-	-	-
828-SS-2-2.5/GSI-SG-2 (2.5)	<5/<5	-	-	-
828-SS-3/GSI-SS-3 (SS)	<5/<5	-	-	-
828-SS-5/Tt-SS-5 (SS)	<5/<5	-	-	-
828-SS-6/Tt-SS-6 (SS)	<50/<50	-	-	-
Tt-SG-1 (groundwater) (16)	-	27,400/8,740	-	-
Tt-SG-2 (groundwater) (19)	-	23,400/6,730	-	-
Tt-SG-3 (groundwater) (15)	-	2,830/770	-	-
Tt-SG-4 (groundwater) (16.5)	-	1,850/<500	-	-
Tt-SG-5 (groundwater) (15)	-	9,010/2,870	-	-
Tt-SG-6 (groundwater) (16)	-	19,400/7,550	-	-
828-SM-1 (Indoor)	-	-	3.9/1.6	-
828-SM-5 (Indoor)	-	-	2.7/1.0	-
828-SM-ODN (Outdoor)	-	-	-	0.022/<0.12

1. The data pairs shown are TCE/cis-1,2-DCE

Table 4-3
Benzene and Toluene Data Collected at Travis AFB (all concentrations μg/m^3)[1]

Sample ID/Location (feet bgs)	Soil Gas	Groundwater	Indoor Air	Outdoor Air
828-SG-1-5/Tt-SG-1 (5)	17/140	-	-	-
828-SG-2-5/Tt-SG-2 (5)	36/170	-	-	-
828-SG-4/Tt-SG-4 (5)	130/260	-	-	-
828-SG-5-5/Tt-SG-5 (5)	79/490	-	-	-
828-SG-6-5/Tt-SG-6 (5)	14/90	-	-	-
828-SS-1/GSI-SS-1 (SS)	<5/16	-	-	-
828-SS-2/GSI-SS-2 (SS)	<5/15	-	-	-
828-SS-2-2.5/GSI-SG-2 (2.5)	<5/15	-	-	-
828-SS-3/GSI-SS-3 (SS)	<5/13	-	-	-
828-SS-5/Tt-SS-5 (SS)	<5/47	-	-	-
828-SS-6/Tt-SS-6 (SS)	<50/2,200	-	-	-
Tt-SG-1 (groundwater) (16)	-	<500/<500	-	-
Tt-SG-2 (groundwater) (19)	-	<500/<500	-	-
Tt-SG-3 (groundwater) (15)	-	<500/<500	-	-
Tt-SG-4 (groundwater) (16.5)	-	<500/<500	-	-
Tt-SG-5 (groundwater) (15)	-	<500/<500	-	-
Tt-SG-6 (groundwater) (16)	-	<500/<500	-	-
828-SM-1 (Indoor)	-	-	0.44/1.3	-
828-SM-5 (Indoor)	-	-	0.42/1.7	-
828-SM-ODN (Outdoor)	-	-	-	0.32/0.33

1. The data pairs shown are benzene/toluene.

Table 4-4
Ethylbenzene and Total Xylenes Data Collected at Travis AFB (all concentrations µg/m^3)[1]

Sample ID/Location (feet bgs)	Soil Gas	Groundwater	Indoor Air	Outdoor Air
828-SG-1-5/Tt-SG-1 (5)	10/57	-	-	-
828-SG-2-5/Tt-SG-2 (5)	19/69	-	-	-
828-SG-4/Tt-SG-4 (5)	16/63	-	-	-
828-SG-5-5/Tt-SG-5 (5)	30/98	-	-	-
828-SG-6-5/Tt-SG-6 (5)	17/58	-	-	-
828-SS-1/GSI-SS-1 (SS)	<5/9.8	-	-	-
828-SS-2/GSI-SS-2 (SS)	<5/9.7	-	-	-
828-SS-2-2.5/GSI-SG-2 (2.5)	<5/9	-	-	-
828-SS-3/GSI-SS-3 (SS)	<5/8.3	-	-	-
828-SS-5/Tt-SS-5 (SS)	<5/19	-	-	-
828-SS-6/Tt-SS-6 (SS)	130/325	-	-	-
Tt-SG-1 (groundwater) (16)	-	<500/<500	-	-
Tt-SG-2 (groundwater) (19)	-	<500/<500	-	-
Tt-SG-3 (groundwater) (15)	-	<500/<500	-	-
Tt-SG-4 (groundwater) (16.5)	-	<500/<500	-	-
Tt-SG-5 (groundwater) (15)	-	<500/<500	-	-
Tt-SG-6 (groundwater) (16)	-	<500/<500	-	-
828-SM-1 (Indoor)	-	-	0.24/0.76	-
828-SM-5 (Indoor)	-	-	0.32/1.0	-
828-SM-ODN (Outdoor)	-	-	-	0.055/0.15

1. The data pairs shown are ethylbenzene/total xylenes.

To better interpret the data in these tables, Figure 4-2 to Figure 4-4 were created to show the data and their spatial distribution. Figure 4-2 focuses on TCE and cis-1,2-DCE in groundwater, indoor air and outdoor air. A general trend exists that indicates both TCE and cis-1,2-DCE are increasing in concentration in the direction of flow, with an approximate ten-fold increase from upgradient to downgradient for both chemicals.

Both TCE and cis-1,2-DCE were sampled indoors at two locations as shown in Figure 4-2. The indoor air concentrations are approximately ten times higher than the outdoor concentrations, and suggest that soil vapor intrusion is occurring. Figure 4-5 provides further supporting evidence for the occurrence of vapor intrusion. This figure shows the similarities of the TCE/cis-1,2-DCE chemical fingerprints of the groundwater samples and in the indoor air samples. The similarities in the chemical fingerprints suggest the chemicals in indoor air may have as their source chemicals in groundwater.

Given the occurrence of TCE and cis-1,2-DCE in groundwater and indoor air, it was unexpected that the soil gas levels of these two chemicals were, all except one, below detection limits (DLs). However, it is possible that concentrations could be present at low concentrations at these locations, and still produce measurable indoor air concentrations, if the attenuation factor between the indoor air and soil gas is close to one, which is highly unlikely.

BTEX concentrations in the soil that are shown in Figure 4-3 and Figure 4-4 do not reveal spatial trends, in contrast to TCE and cis-1,2-DCE. This implies that the source of BTEX may not be from the groundwater, but perhaps from former soil contamination. Since the indoor air BTEX levels are somewhat higher than the outdoor levels and given the occurrence of BTEX in the soil gas around and below Building 828, it is feasible that BTEX vapor intrusion is occurring. Figure 4-6 also shows a general similarity between fingerprints of BTEX in soil gas and indoor air.

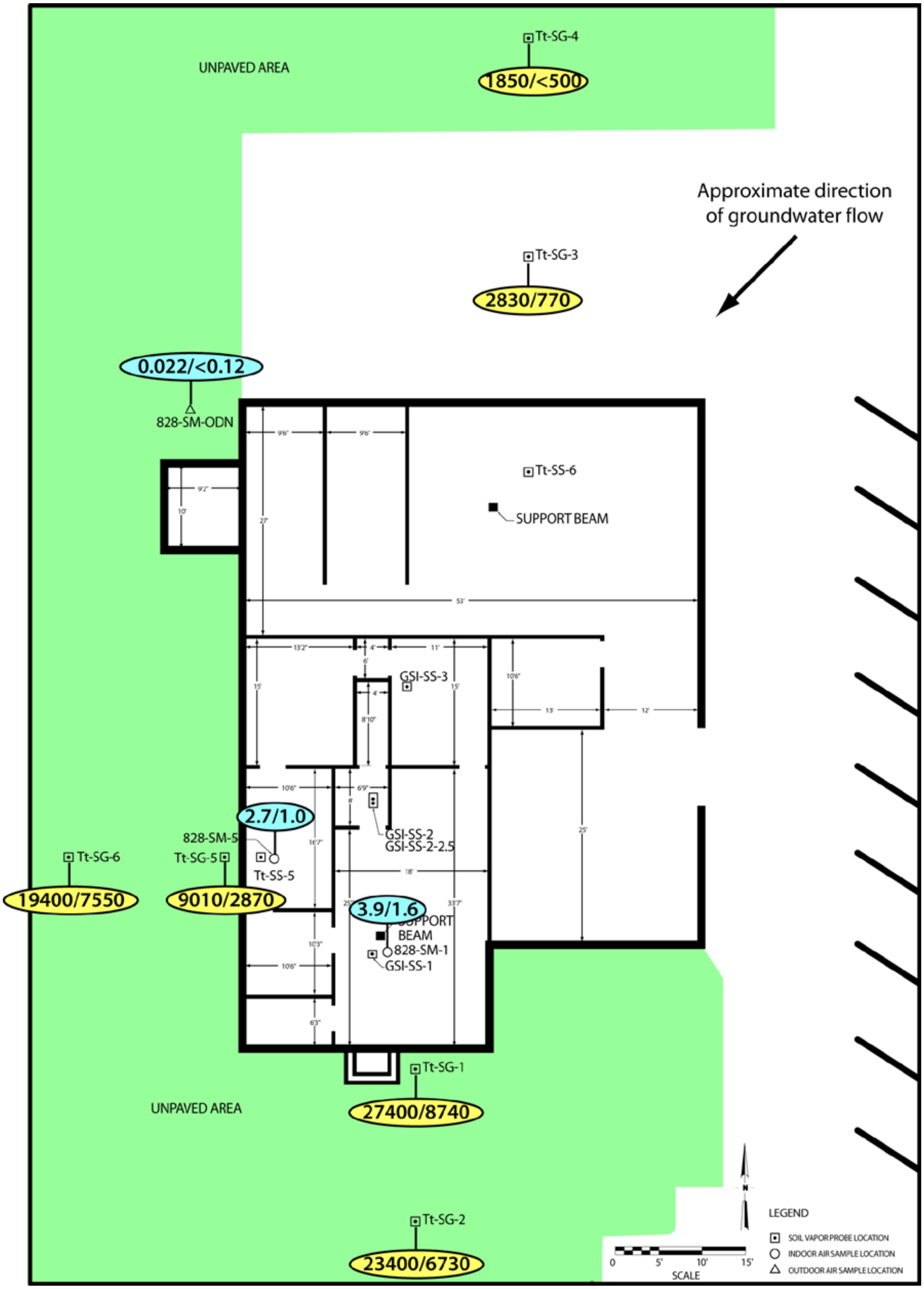


Figure 4-2
Groundwater concentrations (yellow, TCE/cis-1,2-DCE), indoor air concentrations (blue), and outdoor air concentrations (blue) of TCE and cis-1,2-DCE (all concentration units are in µg/m^3)

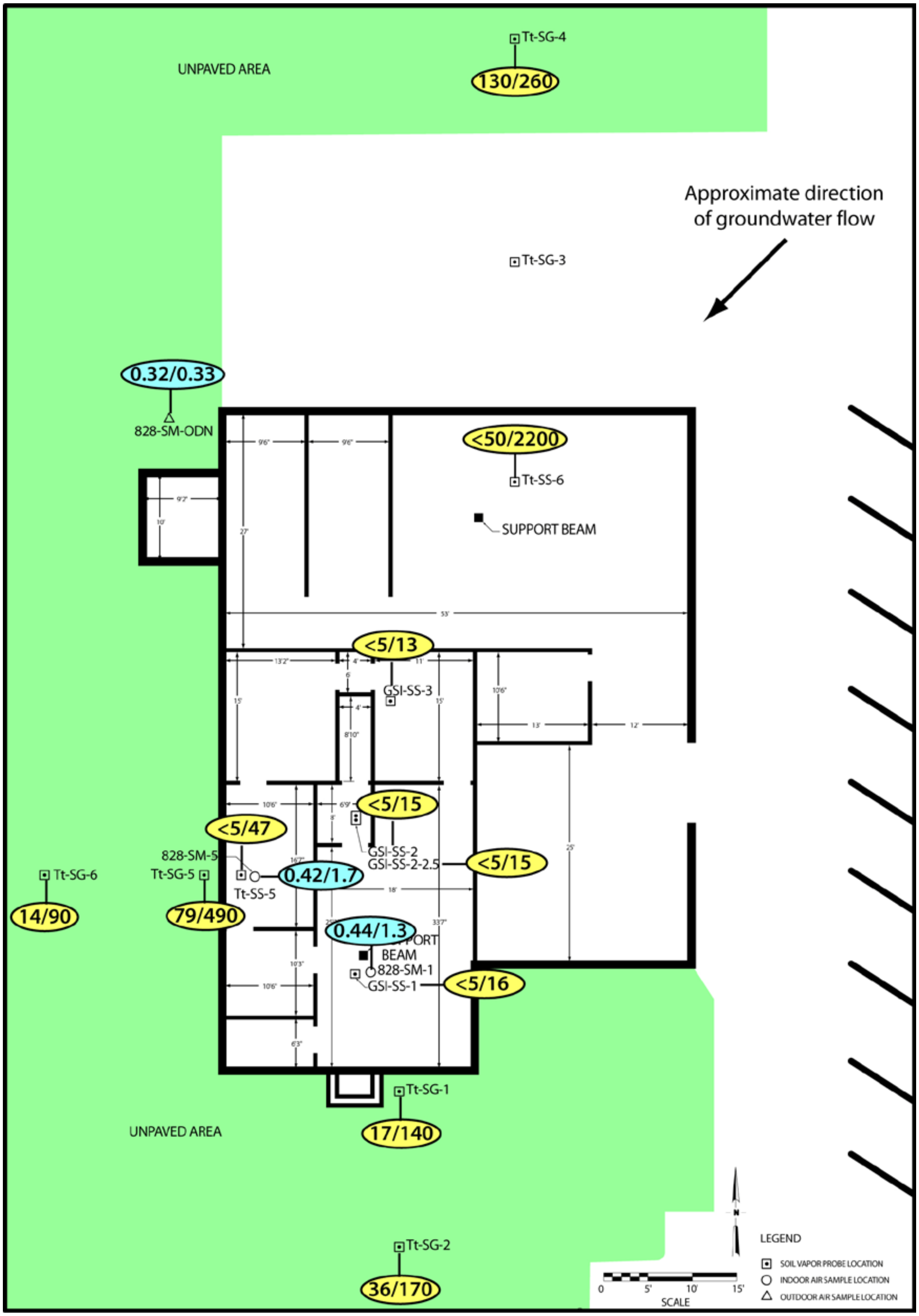


Figure 4-3
Soil gas concentrations (yellow, benzene/toluene), indoor air concentrations (blue), and outdoor air concentrations (blue) for benzene and toluene (all concentrations are in µg/m^3).

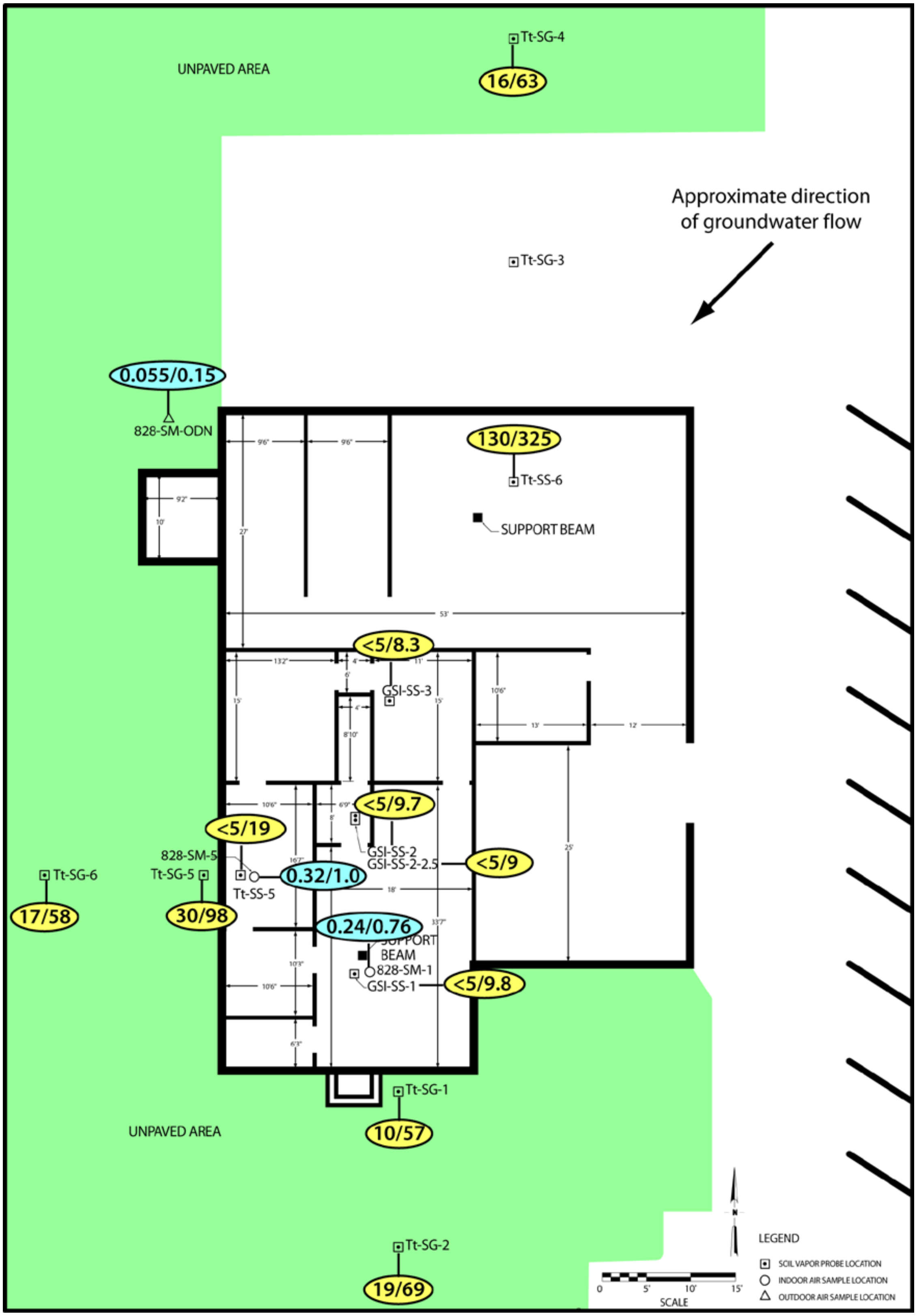
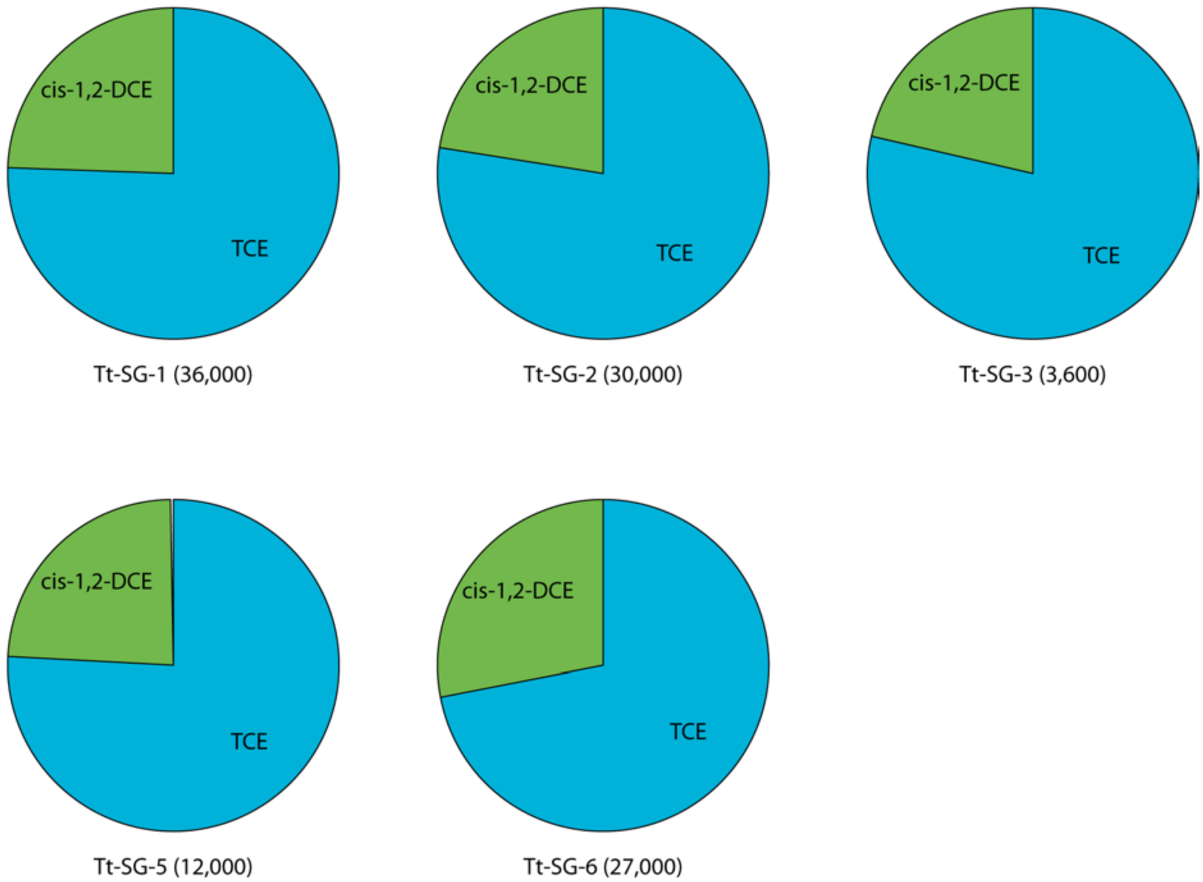


Figure 4-4
Soil gas concentrations (yellow, ethylbenzene/total xylenes), indoor air concentrations (blue), and outdoor air concentrations (blue) for ethylbenzene and total xylenes (all concentrations in μg/m^3).

a) Groundwater distribution by chemical and total concentrations, µg/m³



b) Indoor air distribution by chemical and total concentrations, µg/m³

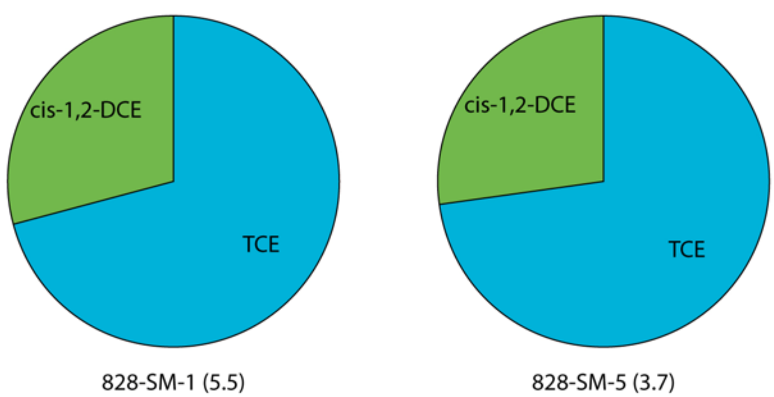
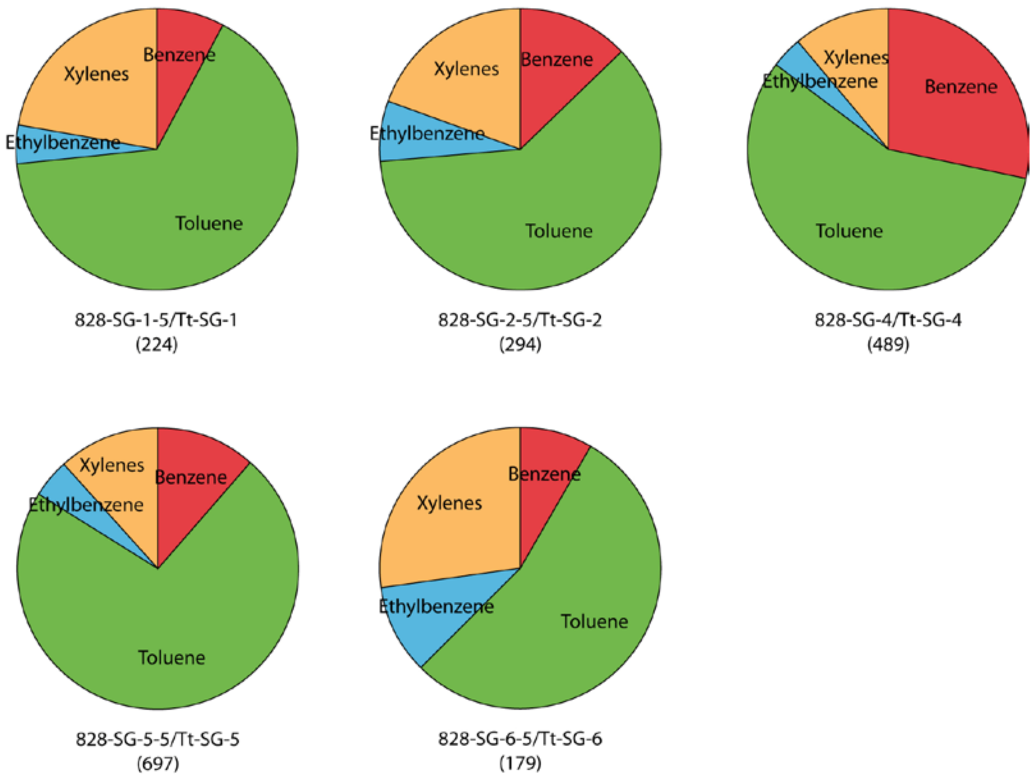
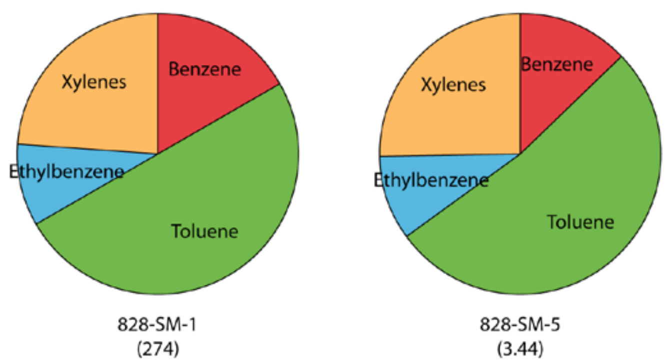


Figure 4-5
TCE and cis-1,2-DCE Groundwater and Indoor Air Concentrations

a) Soil gas distribution by chemical and total concentrations, µg/m³



b) Indoor air distribution by chemical and total concentrations, µg/m³



c) Outdoor air distribution by chemical and total concentrations, µg/m³

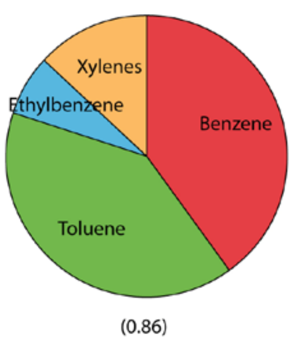


Figure 4-6
Benzene, Toluene, Ethylbenzene, and Xylenes

5 VAPOR INTRUSION MODELING RESULTS

5.1 Background and Approach

Vapor intrusion into Building 828 at TAFB was simulated using two modeling approaches: the J&E Model (Johnson & Ettinger, 1991) and ViM (Mills et al., 2007). Detailed descriptions of each model can be found in these two references. A summary comparison is shown in Table 5-1. The J&E model is the simpler of the two models and assumes a steady-state source term. ViM accommodates a time-variable source term. Another difference in the two models is that ViM has the option of using a Monte Carlo analysis. This feature can be used to create a confidence interval about the predicted results, assuming a range of input data can be reasonably specified.

Table 5-1
ViM and J&E Comparison

Capability	ViM	J&E/EPA
Basements, slab-on-grade	✓	✓
Crawl space	✓	
Multiple compartments	✓	
Outdoor air intrusion	✓	
Non-steady conditions	✓	
Lifetime exposure	✓	✓
Monte Carlo: Uncertainty Analysis	✓	
Chemical Processes: biodecay, adsorption	✓	
Sensitivity Analysis	✓	✓

Modeling simulations have been completed for TCE. Since ViM can simulate five different building configurations (such as one-story buildings with crawl spaces or one-story buildings with slab-on-grade foundations), the appropriate building type for Building 828 was selected (slab-on-grade). Data used by the two models were the same when possible. Examples of the datasets are shown in Appendices G (for ViM) and H (for J&E model).

The J&E modeling results will be shown first, followed by ViM model results. The J&E modeling discussion includes two simulation periods: one conducted in December 2008 when the choice of building for the subsequent field investigation was being evaluated and the J&E model was applied to multiple buildings, and a second application subsequent to the detailed site investigation conducted at Building 828 in March 2009. The ViM model was applied only at Building 828. ViM has embedded within it a version of the J&E model (called JEM) that accepts input data from the same file as does ViM. This ensures that both models are using the same data, and that any differences between the two models are not due to data differences.

5.2 J&E Model Applications

In December 2008, four candidate buildings were being considered for detailed site investigations at Travis AFB: Building 1130, Building 1001, Building 836, and Building 828. As part of the selection process, the J&E model was run at each site, using data available at that time, to see which building(s) offered the greatest probability that indoor air concentrations of TCE would be detectable.

In May 2008 indoor air samples were taken at the four buildings indicated above as part of a preliminary investigation. These results were to be used to subsequently select a building for the detailed 2009 investigation. However, measured indoor air concentrations of TCE at all buildings were low (≤0.29 µg/m^3), and in Building 828 concentrations were below detection limits (see Table 5-2). Because of these low concentrations, it was subsequently decided to tabulate groundwater concentrations of TCE collected in 2006 and 2007, use those data as a source term, and then use J&E to predict indoor air concentrations of TCE. The rationale for doing this was to identify a building where the model predicted that VI should be occurring but that the empirical data suggest it is not occurring. Model predictions are shown in Table 5-2, along with the groundwater concentrations at nearby wells, and the indoor air concentrations measured in May 2008. The overall result was that predicted concentrations of TCE in indoor air were highest in Building 1001 and in Building 828, while the measured concentration was lowest in Building 828 (Table 5-2). Based on these findings and on logistical considerations, Building 828 was selected for the 2009 detailed investigation. Table 5-3 shows the input data used in the model for the simulation. When available, site-specific data were used.

For the 2009 site investigation, the Johnson and Ettinger Model was again used to model migration of TCE vapors from groundwater into indoor air for Building 828. The range of groundwater concentrations (1,850 to 27,400 µg/m^3) detected at sampling locations around the building (SG-1 through SG-6) were modeled. Input data for the model are shown in Appendix F.

Predicted indoor air concentrations of TCE ranged from 0.0015 to 0.02 µg/m^3 based on the 2009 groundwater concentrations (1,850 to 27,400 µg/m^3). These predicted concentrations are 100 times lower than the indoor air concentrations measured in Building 828 in March 2009 (3.9 µg/m^3 at SM-1 and 2.7 µg/m^3 at SM-5) as shown previously in Figure 4-2. The predicted concentrations based on 2006 and 2007 groundwater data shown in Table 5-2 (0.63 to 16.6 µg/m^3) are more comparable to the 2009 measured indoor air concentrations. Major differences in the model inputs between the two applications of the J&E model include the TCE concentration in groundwater, the depth to groundwater, and the soil type. Also the J& E model assumes background concentrations are zero, which is not the case for this site (0.022 µg/m^3). The differences in model input reflect the availability of site specific data. For the first application of the J&E model, groundwater concentrations used as input (65,000 to 1,200,000 µg/m^3) were taken from existing data from groundwater monitoring wells in the vicinity of the site, whereas for the second application data from grab samples collected immediately adjacent to Building 828 were used (1,850 to 27,400 µg/m^3). The depth to groundwater used for the first application was extrapolated from nearby monitoring wells and estimated to be approximately 10 feet bgs, whereas site specific data indicated the depth to groundwater at the time of the March 2009 investigation was on the order of 16 feet bgs. Similarly, based on nearby monitoring wells, the soil type was previously assumed to be silty clay loam, whereas the site specific data collected in March indicate the soils beneath the building are clay.

Table 5-2
TCE Concentrations at Travis AFB Near Four Buildings
(see footnote for explanation of yellow highlighting)

Well ID[1]	Sampling Date	Concentration in Groundwater ($\mu g/m^3$)	J&E Predicted Indoor Air Concentration ($\mu g/m^3$)	Sampled Indoor Air Concentration in Each Building (5/14/08 sampling date) ($\mu g/m^3$)	Notes
Monitoring Wells Near Building 1130					
EW04X29 (100 ft)	11/2/2006	210,000	1.9	0.29	Communication Transmitter. Occupied.
EW05X29	11/10/2006	58,000	0.52		
MW05X29	5/9/2007	ND	-		
MW04X29	5/7/2007	280	0.0025		
Monitoring Wells Near Building 1001					
MW327X16 (70 ft)	5/11/2007	1,800	0.018	0.11	Engine Test Cell. Occupied.
MW214X16 (90 ft)	5/11/2007	2,000,000	19.6		
MW305X16 (90 ft)	5/10/2007	920	0.0090		
MW102X16 (125 ft)	11/6/2006	79,000	0.77		
MW102X16 (125 ft)	5/11/2007	99,000	0.97		
EW003X16	11/6/2006	62,000,000	608		
Monitoring Wells Near Building 835					
EW702X37 (20 ft)	11/9/2006	17,000	0.16	0.028	Squadron Operations.
MW526X37 (100 ft)	5/22/2007	200,000	1.9		
MW514X37 (60 ft)	5/22/2007	11,000	0.10		
MW523X37 (50 ft)	11/9/2006	60,000	0.57		
MW523X37 (50 ft)	5/22/2007	260,000	2.5		
EW701X37	11/9/2006	140,000	1.3		
MW531X37	5/24/2007	710,000	6.7		
Monitoring Wells Near Building 828					
EW599X37 (150 ft)	11/9/2006	1,200,000	11.7	<0.028	Security Force Operations. On Demolition List. Occupied.
MW528X37	5/23/2007	95,000	0.93		
MW524X37	5/24/2007	1,700,000	16.6		
MW540X37	5/30/2007	94,000	0.92		
MW539X37	5/22/2007	65,000	0.63		

[1]Wells within 150 ft of edge of building are highlighted in yellow.

Table 5-3
Input Data for the Johnson and Ettinger Model

Parameter Name in JE	Units	Building 828	Building 836	Building 1001	Building 1130
Average soil/gw temperature	deg C	16.7	16.7	16.7	16.7
Depth below grade to bottom of closed space floor	cm	15	15	15	15
Depth below grade to water table	cm	305	321	284	559
SCS Soil type directly above water table	-	Sandy loam	Sandy loam	Sandy loam	Sandy loam
SCS soil type used to estimate vapor permability	-	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Dry bulk density	g/cm^3	1.62	1.62	1.62	1.62
Soil total porosity	cm^3/cm^3	0.387	0.387	0.387	0.387
Water-filled porosity	cm^3/cm^3	0.103	0.103	0.103	0.103
Enclosed space floor thickness	cm	15	15	15	15
Soil-building pressure differential	$g/cm\text{-}s^2$	40	40	40	40
Floor length	cm	1000	1000	1000	1000
Floor width	cm	1000	1000	1000	1000
Height	cm	266	266	266	266
Indoor air exchange rate	1/hr	1	1	1	1
Average vapor flow rate into bldg	L/min	5	5	5	5
Crack to total area ratio	-	0.005	0.005	0.005	0.005

5.3 ViM Model Applications

Since ViM can simulate the effects of a time-variable groundwater plume, Figure 5-1 was developed to provide estimates of groundwater concentrations not only in 2009 (when the site investigation was done), but also in 2006-2007 when groundwater concentrations in the vicinity of Building 828 may have been higher as suggested by the data in Table 5-2. However, differences in locations of samples, depths to water table, and sampling methodology may have all played a role in the differences in measured groundwater concentrations between these two time periods, and the evidence is certainly not conclusive that concentrations beneath Building 828 were actually higher in 2007-2008.

Using these data, indoor air and subslab concentrations were predicted for both ViM and JEM. See Figure 5-2. It is noticed that ViM predicted concentrations while initially very low, eventually exceed JEM predictions beginning in 2008 and continuing until 2014. Given that JEM is a steady-state model, this behavior was not expected, but is explained as follows. The groundwater concentration used in the JEM predictions corresponded to the upper end of the observed groundwater data collected in 2009, which was 27,400 $\mu g/m^3$. While the ViM model used the same groundwater concentration for 2009, earlier concentrations in 2006-2007 may have been higher as shown previously in Figure 5-1. During that time vadose zone vapors were predicted to have been migrating through the unsaturated zone (Figure 5-3), and it was these vapors that caused the predicted indoor air concentrations to be higher than the JEM predictions.

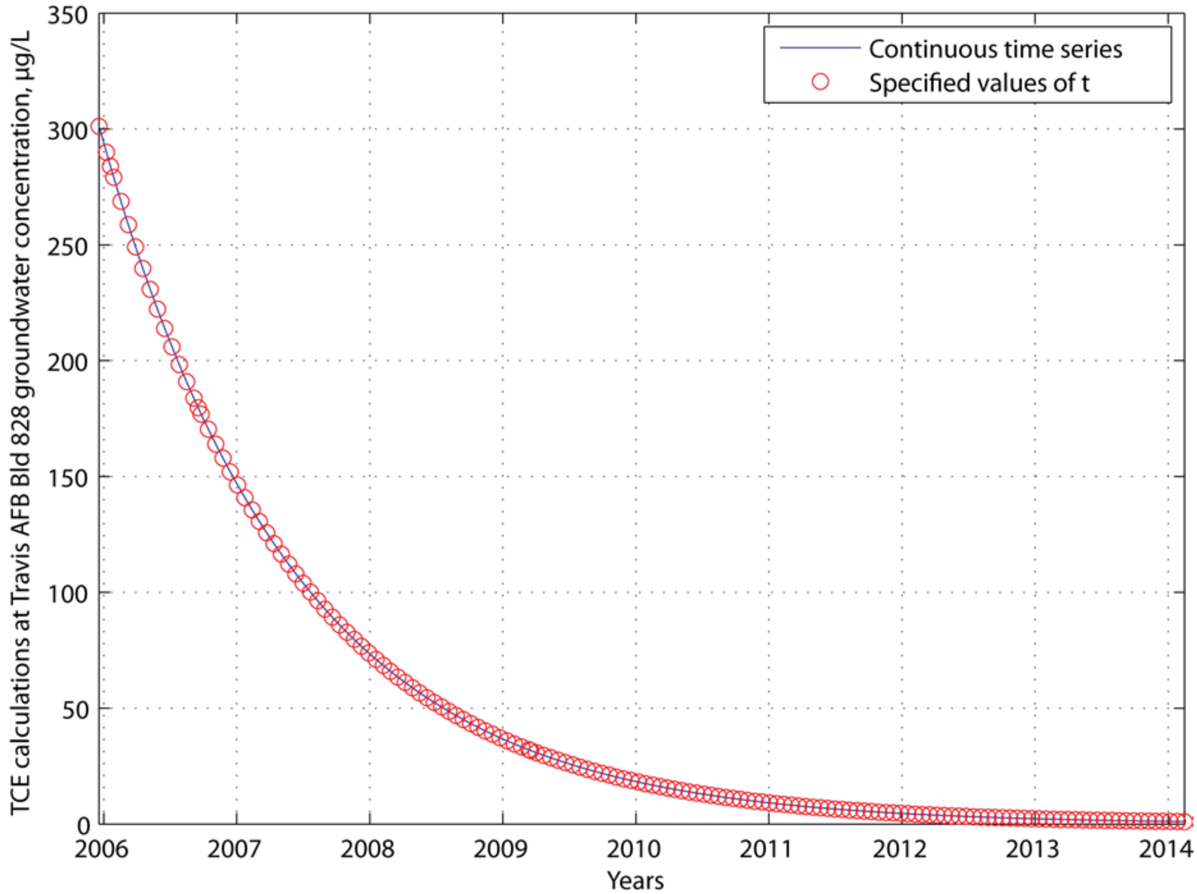


Figure 5-1
Time series of groundwater TCE concentrations at Travis AFB, in the vicinity of Building 828

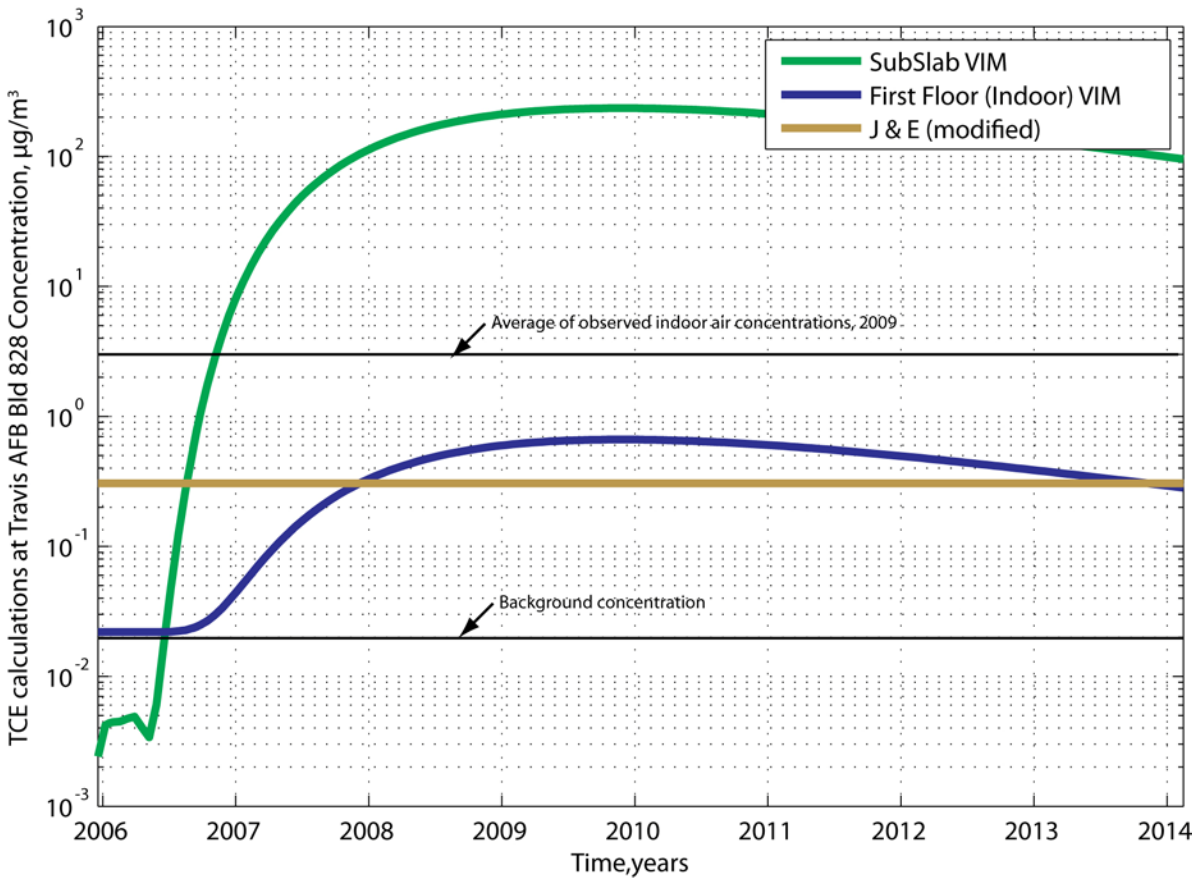


Figure 5-2
TCE concentrations at Travis AFB Building 828

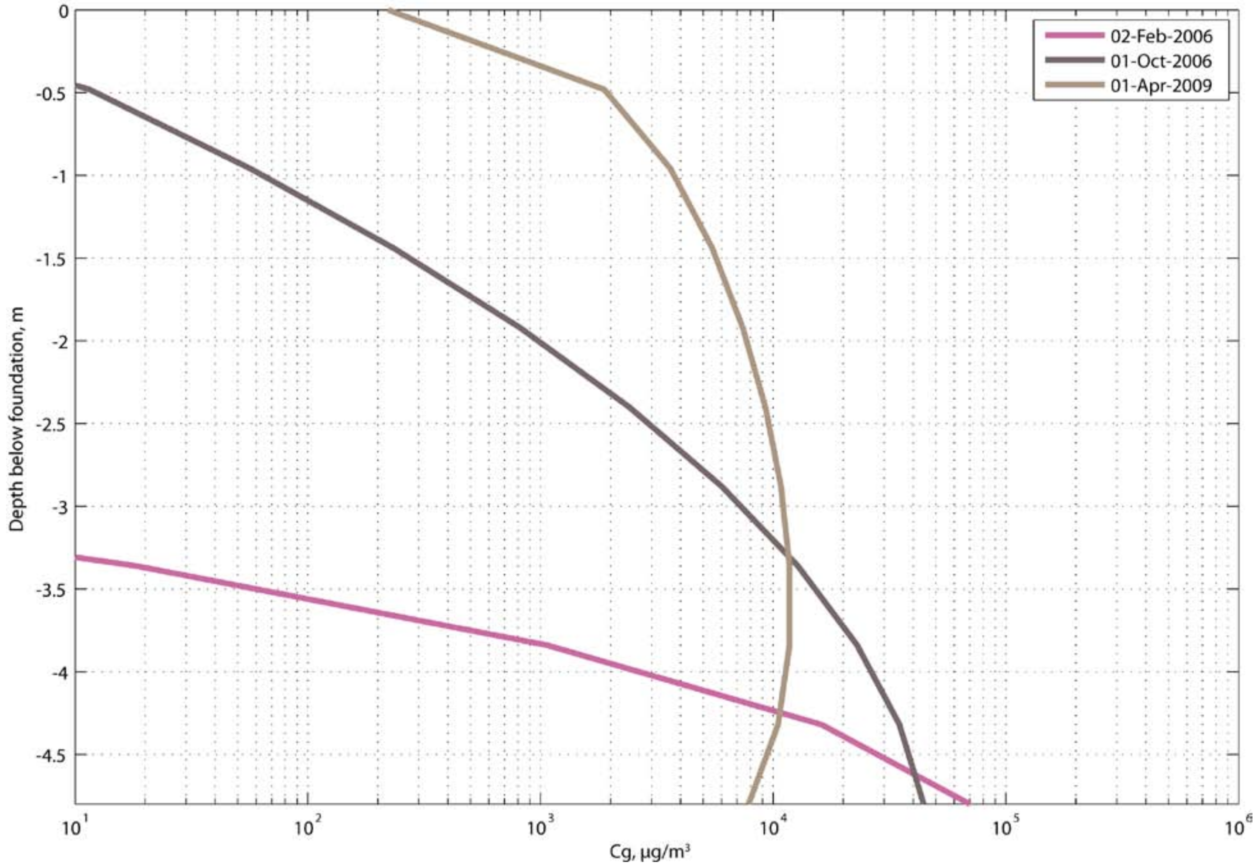


Figure 5-3
Predicted profiles of subsurface vapor phase concentrations between groundwater and foundation for TCE calculations at Travis AFB Building 828

An interesting feature about the predictions in Figure 5-2 in that the predicted subslab concentrations are much higher than the observed subslab data, while predicted indoor air concentrations are lower than the observed data. Observed subslab concentrations were non-detect with detection levels between 5 µg/m^3 and 50 µg/m^3, while the predicted subslab concentrations exceeded 100 µg/m^3 in 2009. The reason for this discrepancy is not known. However, given indoor air concentrations of 2.7 to 3.9 µg/m^3, and typical attenuation factors for subslab to indoor air of 0.01 to 0.1, it was expected that subslab vapor concentrations would be in the range of 30 to 390 µg/m^3.

In an attempt to explain this behavior, ViM and JEM were both rerun with smaller effective soil diffusion coefficients in the unsaturated zone to simulate a less permeable soil profile. The predictions are shown in Figure 5-4. The indoor air concentrations are initially 0.02 µg/m^3, which are the ambient concentrations specified from observed data. For this simulation scenario, the predicted indoor air concentration only increases to about 0.04 µg/m^3, which is two times the ambient concentration. The indoor air concentration data are shown in Figure 5-4 by the top dashed red line, and indicate the significant difference between observations and predictions.

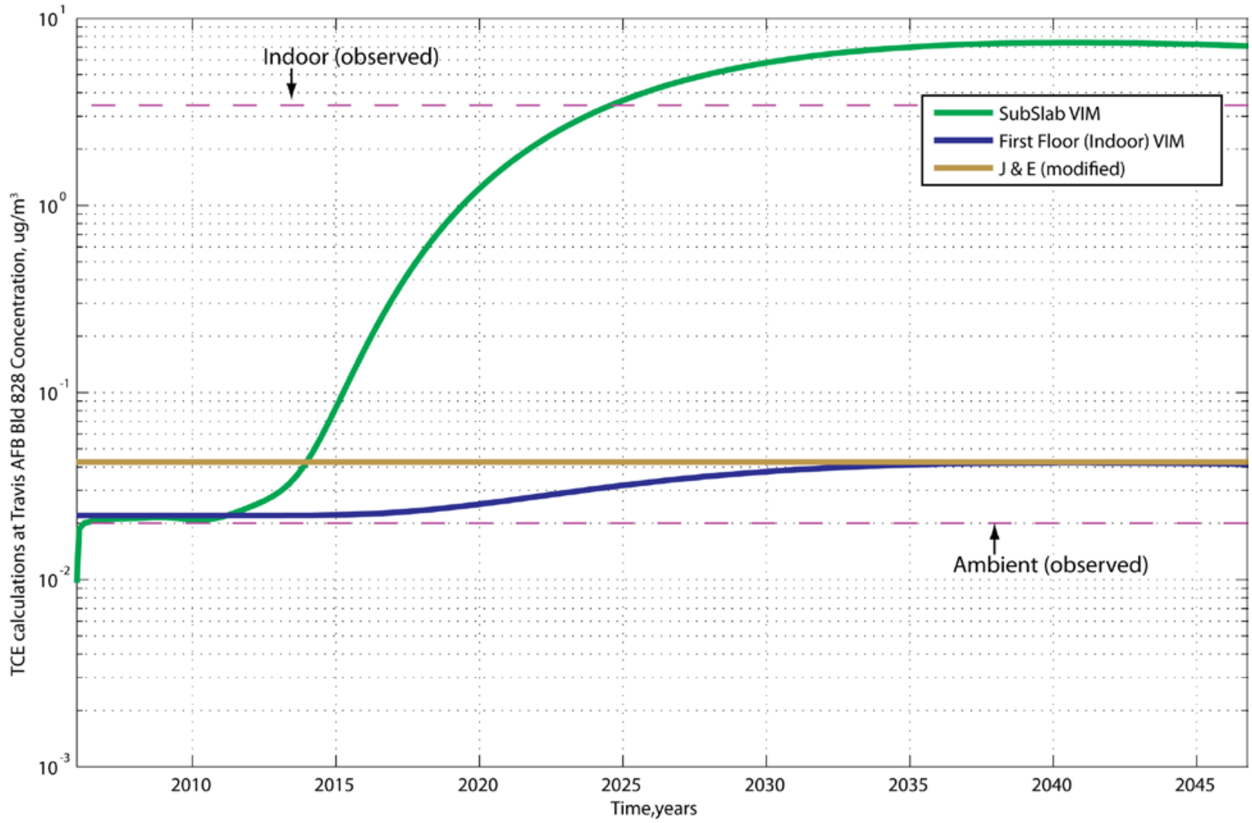


Figure 5-4
Indoor and subslab TCE concentrations for low soil diffusion coefficients

The subslab concentrations for this prediction are generally well below detection limits (<5 μg/m^3), consistent with the observed data collected at the subslab location. These results reinforce the earlier statements that the models do not predict both subslab and indoor air concentrations accurately. Possible reasons for this behavior include the following:

- A preferential pathway exists from the subslab to indoor air, where vapor intrusion is occurring over only a small fraction of the foundation, and has not been detected
- An indoor source of TCE is present in the building
- The groundwater TCE concentrations are fluctuating more rapidly (at higher frequency) than can be quantified by the available data, sending unsteady pulses of vapor through the unsaturated zone.
- Heavy rainfall prior and during the first part of the 2009 field investigation. Figure 5-5 shows the heavy precipitation in February and early march 2009. Infiltrating and perched water may have influenced field study results.

The few data points (in Table 5-2 and Table 4-2) show that the TCE concentrations in groundwater fluctuate between 1,850 μg/m^3 to about 1,700,000 μg/m^3 from 2007 to 2009 at locations adjacent to Building 828, but not always directly adjacent to it. Large groundwater concentration differences can produce soil vapor concentration differences, thus helping to explain some of the seemingly aberrant behavior.

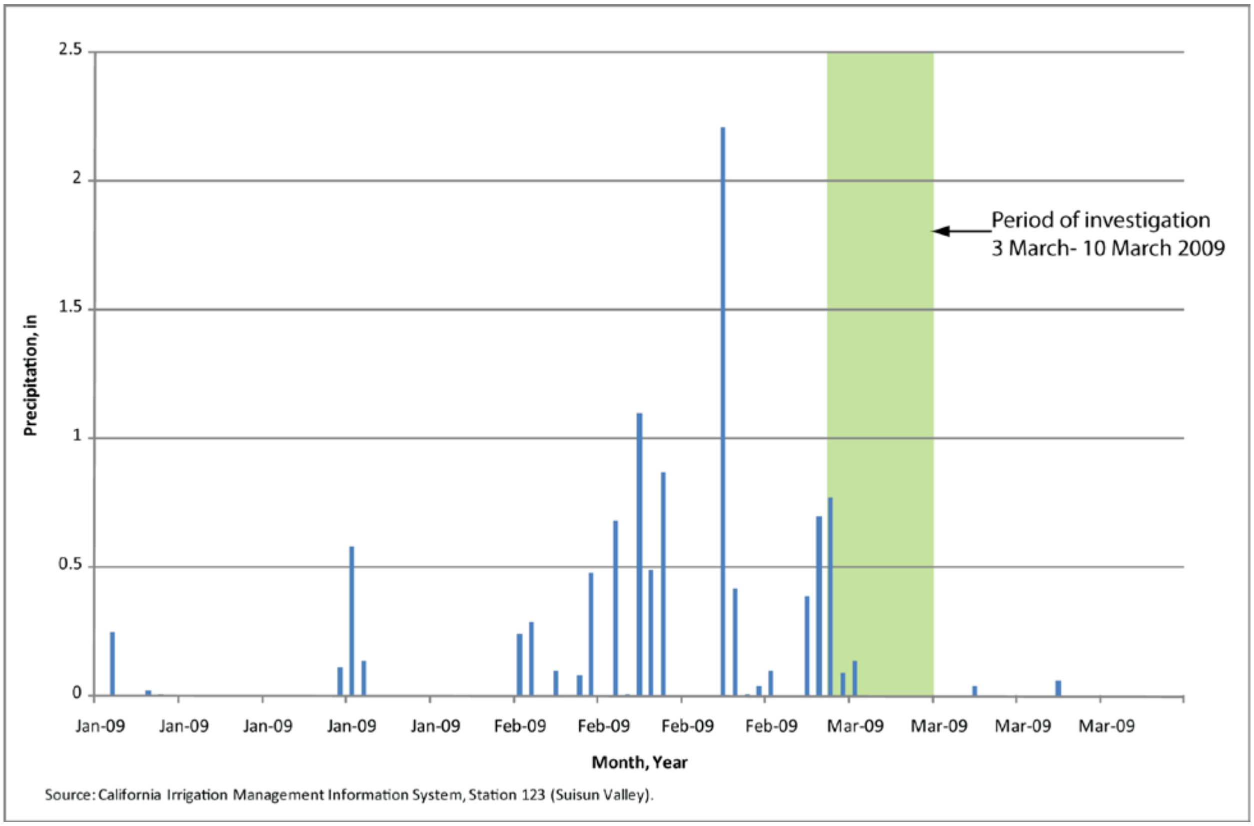


Figure 5-5
Daily Precipitation near Travis AFB

6 CONCLUSIONS

The major conclusions of this work are:

1. The air exchange rate (AER) for Building 828 was successfully calculated and ranged between 13/day to 17/day using an instantaneous release of a known quantity of helium. The methodology for doing this was developed for this project, and results to date indicate the method is reliable, easy to deploy, and inexpensive.
2. Concentrations of TCE and cis-1,2-DCE were consistently detected in the groundwater and in the indoor air. Indoor air concentrations for TCE were between 2.7 to 3.9 µg/m^3, and for cis-1,2-DCE ranged between 1.0 to 1.6 µg/m^3. However sub-slab soil gas concentrations for TCE and cis-1,2-DCE were all below detection levels (typically 5 µg/m^3). The fact that TCE and cis-1,2-DCE were not detected at sub-slab locations does not support the notion of vapor intrusion through the subslab. However, it is possible that a preferential pathway through the slab exists, or an indoor source of these chemicals is present.
3. BTEX compounds were detected in suslab and deep soil gas locations and in indoor air, but were not detected in groundwater. The detection limit in groundwater was 500 µg/m^3 and was considerably above levels detected in soil vapor. The absence of detectable BTEX in groundwater and its presence in soil gas and indoor air suggests the presence of a soil source of BTEX.
4. In the J &E model simulations performed prior to the March 2009 field investigation and shown in Table 5-2, some of the model predicted indoor air concentrations were higher than the indoor air concentrations collected on May 14, 2008, and suggested that VI should have been occurring while the data suggested otherwise. Subsequent to the March 2009 field investigation, soil borings showed the soil type in the vicinity of the building was clay, and had that soil type been used as input to the J&E model, the predicted indoor air concentrations would have decreased (specific amounts is not known).
5. Soil vapor intrusion simulations were completed for both the J&E and ViM models for TCE using the groundwater TCE data as the source term. The modeling results were not able to completely explain the observed TCE behavior. Given that the observed indoor air TCE concentrations were about half the detection level for the sub-slab samples and considering typical sub-slab attenuation factors of 0.01 to 0.1, the modeling results strongly suggested that sub-slab concentrations should have been well above the detection level of 5 µg/m^3. Otherwise, different explanations for the indoor air vapor concentrations such as preferential pathways, an indoor source of TCE, or influences of previous high intensity rainfall events could provide an explanation.
6. Following on from conclusion #4,the results of the grab groundwater sampling for this investigation indicated considerably lower concentrations as compared to the groundwater monitoring program data from 2006-2007. This discrepancy may simply represent temporal variations in concentration, however, a two order-of-magnitude decrease in concentration over 2 years seems unlikely. An alternative explanation is that the samples collected for this investigation were obtained from the top of the groundwater column whereas the monitoring well samples from 2006-2007 are representative of a much longer vertical section of the

groundwater column. If this is the case, it has important implications for use of groundwater sampling data in predicting the potential for vapor intrusion to occur.

7 REFERENCES

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Mills, William B.; Liu, Sally; Rigby, Mark C.; and Brenner, David (2007) Time-Variable Simulation of Soil Vapor Intrusion into a Building with a Combined Crawl Space and Basement. *Environmental Science & Technology* Vol. 41, No. 14., p 4993–5001