INTERIM REPORT

Integrated Field-Scale, Lab-Scale, and Modeling Studies for Improving the Ability to Assess the Groundwater to Indoor Air Pathway at Chlorinated Solvent-Impacted Groundwater Sites

SERDP Project ER-1686

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Table of Contents

Objectives 1
Technical Approach 2
Field-scale Studies 2
Modeling Studies 6
Results and Discussion 6
Indoor Air Concentration Changes with Time 6
Groundwater Concentration Changes with Time and Depth to Groundwater 8
Soil Gas Contour Plots 9
Soil Gas Concentration Changes with Time 13
Real-Time Monitoring of Indoor Air Radon Concentrations with Time 14
Radon Concentrations in Soil Gas 15
Real-Time Monitoring of SF_6 in Indoor Air 16
Soil Gas Monitoring of SF_6 18
Conclusions to Date 18
Literature Cited 20

List of Tables

Table 1. Sampling network specifics....4
Table 2. Measurements, analytical methods, instruments used and data generated at the study house since February 2010....5

List of Figures

Figure 1. Location of study home relative to TCE plume and photo from street level....3
Figure 2. Conceptual schematic of monitoring conducted at field laboratory house site....3
Figure 3. Plan view layout of in situ monitoring point locations....4
Figure 4. Indoor air monitoring data, with color blocks denoting seasons....7
Figure 5. Expanded views of temporal indoor air concentration behavior in Summer 2010 and Fall 2011....7
Figure 6. TCE concentration changes with time for the shallowest groundwater samples collected beneath the foundation, and groundwater elevation and precipitation vs. time....9
Figure 7. Sample TCE soil gas contours [ppb_v] at 6-ft below the foundation for six of the thirteen snapshot sampling events....10
Figure 8. Sample TCE soil gas contours [ppb_v] at 3-ft below the foundation for six of the thirteen snapshot sampling events....11
Figure 9. Sample TCE soil gas contours [ppb_v] at sub-slab depth for six of the thirteen snapshot sampling events....12
Figure 10. TCE soil gas concentrations vs. time at two depths and two locations....13
Figure 11. TCE and radon indoor air concentrations vs. time....14
Figure 12. Radon soil gas concentration contours [pCi/L]....15
Figure 13. SF_6 in indoor air with a constant 5 mL/min release rate. For reference, 1000 ppb_v corresponds to about 18 indoor air exchanges per day....16
Figure 14. SF_6 in sub-slab soil gas resulting from constant 5 mL/min indoor release rate....17

List of Acronyms

AFB	air force base
DCA	dichloroethane
DCE	dichloroethene
DoD	Department of Defense
GC	gas chromatography
GC-DELCD	gas chromatography – dry electrolytic conductivity detector
GC-ECD	gas chromatography – electron capture detector
GC-MS	gas chromatography – mass spectrometry
MLE	multiple lines of evidence
PCE	perchloroethene (tetrachloroethene)
QA/QC	quality assurance/quality control
SERDP	Strategic Environmental Research Defense Program
TCA	trichloroethane
TCE	trichloroethene
USEPA	United States Environmental Protection Agency
VI	vapor intrusion

Acknowledgements

We would like to acknowledge the financial and logistical support, and encouragement provided by SERDP and Hill Air Force Base's Environmental Restoration Branch, as these have been critical to the success of this project.

Objectives

The SERDP Statement-of-Need ERSON-09-03 sought fundamental and applied research leading to improved assessment of the groundwater to indoor air exposure pathway at chlorinated solvent-impacted groundwater plume sites. It reflected an increasing awareness of the vapor intrusion (VI) pathway, and its significance at Department of Defense (DoD) sites. This pathway is now the risk and clean-up driver at many dissolved chlorinated solvent groundwater plume sites, especially those sites where groundwater plumes have migrated beneath buildings or to areas where future development is planned.

Guidance for assessment of this exposure pathway is variable across federal, state, and local levels. Most documents reflect the evolution of federal guidance toward multiple-lines-of-evidence (MLE)-based approaches that involve indoor air, sub-slab soil gas, deeper soil gas, groundwater and soil sampling in combination with screening-level modeling and empirical assessment (e.g. USEPA 2002). Overall, the basic data requirements for pathway assessment have been increasing with time, and the MLE data interpretation and decision-making are becoming more conservative and complex. This reflects experiences with conflicting lines-of-evidence at some sites, low confidence in our ability to correctly interpret the data, and a limited peer-reviewed knowledge base to rely upon. This may also hint at potential limitations of assessment paradigms that rely too heavily on a few point-in-time and point-in-space discrete samples.

Consistent with ERSON-09-03, the overall objectives of this project are to gain a better understanding of the utility and limitations of the current vapor intrusion pathway assessment approaches, and to identify pathway assessment options that can lead to greater cost effectiveness and increased confidence in VI pathway assessment decisions. The activities involve integrated field-scale, lab-scale, and modeling studies. Technical objectives and key tasks include:

(1) Review of available data and purchase of a house overlying a dissolved chlorinated solvent plume (*Tasks 1.1, 2.1, 3.1, and 4.1 completed*[1]).
(2) Installation of multi-level nested soil gas sampling ports, multi-level discrete groundwater sampling ports and monitoring wells, and analytical instrumentation in the house (*Tasks 1.2, 2.2, 3.2, and 4.2 completed*).
(3) Develop and test all analytical methods used in the study (*completed*).
(4) Initiate and continue real-time sampling and/or monthly sampling of indoor air, soil gas, groundwater, weather conditions, and building characteristics under natural weather conditions for one year (*Tasks 1.3, 2.3, 3.3, and 4.3 completed*).
(5) Release indoor air source and monitor its resulting behavior with time under natural conditions *(Task 6 completed)*
(6) Initiate and continue rigorous data analysis and data mining (*ongoing*).
(7) Initiate and continue numerical modeling of spatial and temporal variability of vapor intrusion using site-specific data (*ongoing*).
(8) Initiate and continue technology transfer of results (*ongoing*).

[1] - tasks as defined in SERDP Project Plan for ER-1686

(9) Initiate and continue real-time sampling and/or monthly sampling of indoor air, soil gas, groundwater, weather conditions, and building characteristics under manipulated conditions (*Tasks 1.4, 1.5, 2.4, 2.5, 3.4, 3.5, 4.4, 4.5, 5.0 to be initiated in June 2012*).

(10) Laboratory studies of groundwater emissions *(to be initiated July 2012).*

This interim report focuses on the technical activities, data collected and significant findings from the first 18 months of research, which were focused on Tasks 1, 2, 3, 4, and 6 in the SERDP Project Plan. This mainly involved monitoring the study home and the underlying soil gas and groundwater under natural conditions, with mechanical air conditioning and heating systems operating at typical residential set-points during this time period.

Technical Approach

As discussed above, this project involves integrated field-scale, lab-scale, and modeling studies. This report emphasizes the field-scale and modeling studies conducted to date. The laboratory-scale physical model studies will begin mid-2012.

Field-scale Studies

A unique element of this project and our approach is that a two-story single-family house was purchased and instrumented to serve as a field-scale vapor intrusion laboratory. The house ("Sun Devil Manor") is located in a residential neighborhood overlying a dilute (<50 ug/L) dissolved chlorinated solvent groundwater plume as shown below in Figure 1. Prior to purchase for this study, routine indoor air monitoring data collected by Hill Air Force Base personnel suggested that the home might experience periodic measurable vapor intrusion impacts to indoor air. The house is equipped with a sub-slab depressurization system that has been sealed off for this first phase of the study, but might be useful in later phases of this study.

The house has been instrumented to allow high-frequency real-time monitoring of indoor air, building characteristics (e.g., pressure differentials, exchange rate), and weather (e.g., wind, temperature, precipitation) and periodic spatially-distributed synoptic sampling "snapshots" of soil gas and groundwater concentrations and depth to groundwater.

Figure 2 conceptually presents a generic vertical cross section showing the vapor intrusion pathway and monitoring components used in this study. Figure 3 shows a plan-view of the areal arrangement of the monitoring network installed at the study house.

Table 1 summarizes specifics of the sampling depths at the locations shown in Figure 3. The sampling locations and sampling depths were selected to reasonably delineate the vapor profile and soil gas concentrations beneath and adjacent to the foundation. Table 2 summarizes key measurements, sampling frequencies, analytical methods developed and tested, and quality assurance/quality control (QA/QC) information for data generated since August 2010.

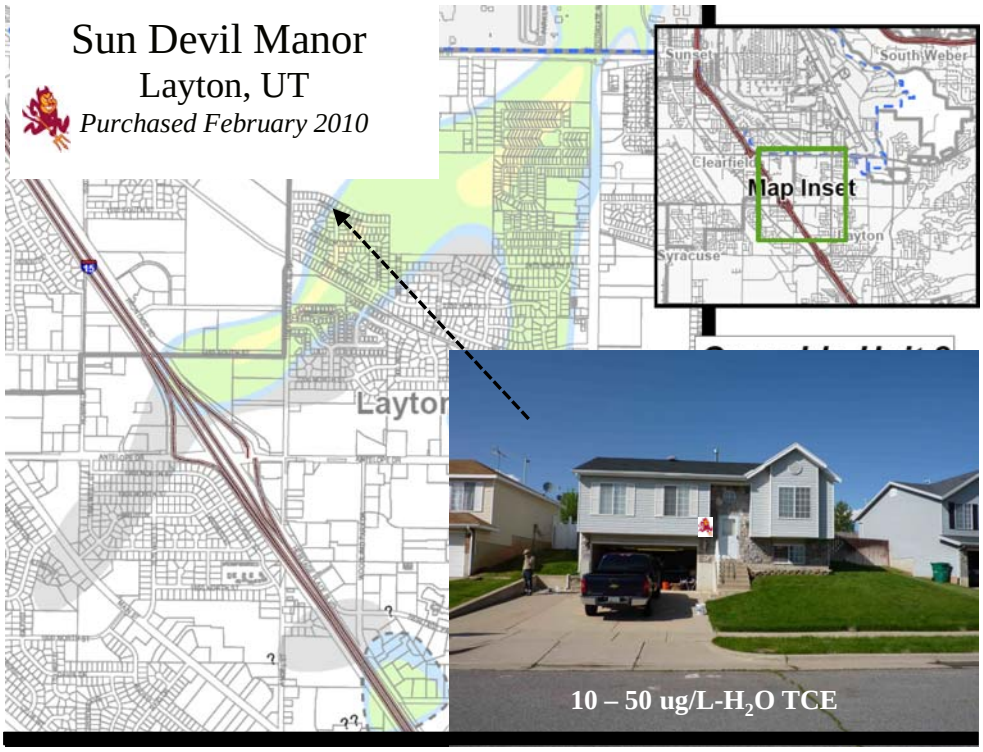
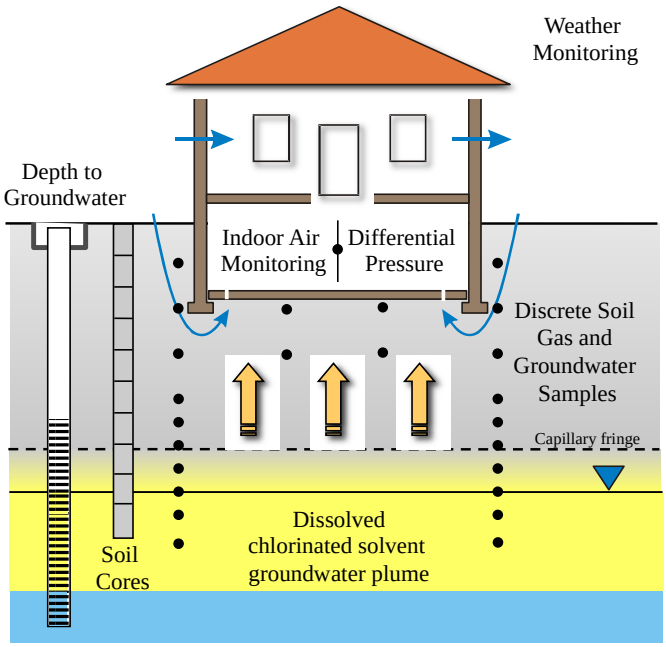


Figure 1. Location of study home relative to TCE plume and photo from street level.



Not shown: in situ effective diffusion coefficient measurements at discrete monitoring points and tracer gas introduction to, and monitoring in, indoor air

Figure 2. Conceptual schematic of monitoring conducted at the field laboratory house site.

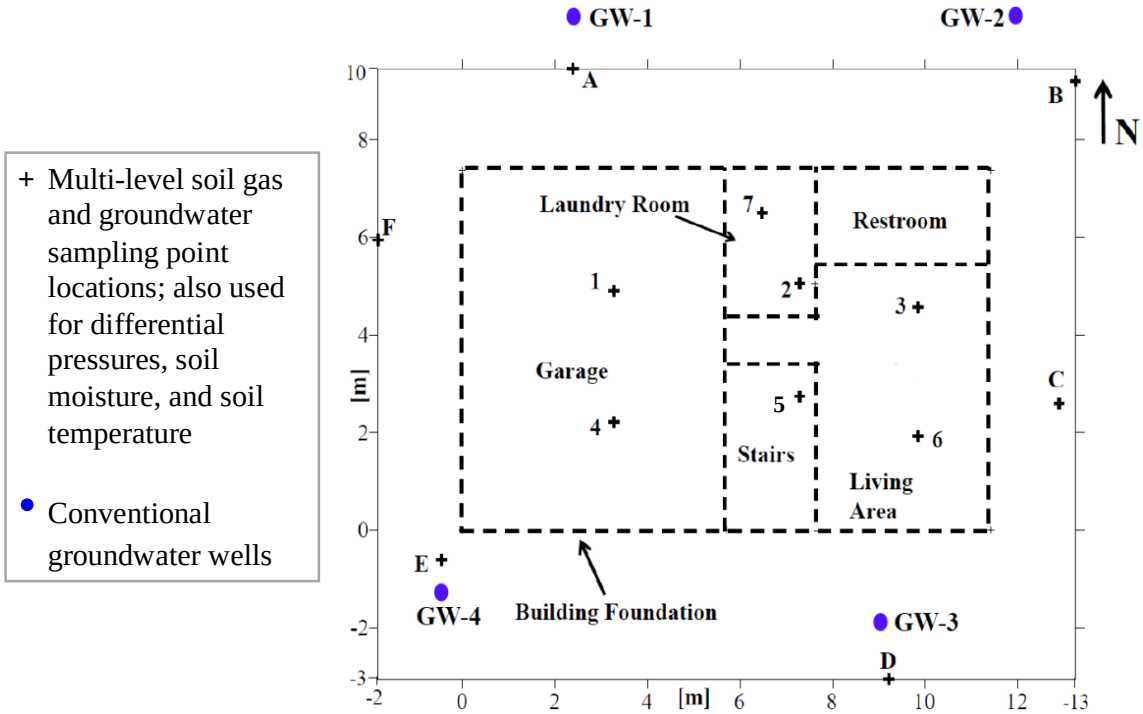


Figure 3. Plan view layout of in situ monitoring point locations.

Table 1. Sampling network specifics (see Figure 3 for locations).

Soil Gas Sampling					Groundwater Sampling			
Location	Depth [ft Below Slab]				Location	Depth [ft BGS]		
A	SS	3	6	9	GW1	16	33	42
B	SS	3	6	9	GW2	16	33	42
C	SS	3	6	9	GW3	14	23	30
D	SS	3	6	9	GW4	13	21	30
E	SS	3	6	9	IGW1	9*	9*	9*
F	SS	3	6	9	IGW2	9*	9*	9*
1	SS	3	6	9*	IGW3	9*	9*	9*
2	SS	3	6	9*	IGW4	9*	9*	9*
3	SS	3	6	9*	IGW5	9*	9*	9*
4	SS	3	6	9*	IGW6	9*	9*	9*
5	SS	3	6	9*				
6	SS	3	6	9*				
7	SS							

* water-saturated conditions sometimes exist at gas sampling 9 ft below-slab depths, and may be used as groundwater sampling points labelled as IGW1-9*, IGW2-9*, etc.

Table 2. Measurements, analytical methods, instruments used and data generated at the study house since February 2010.

Key site measurements	Data generation duration	Analytical methods and frequqncy	Sampling media and location	Data QA/QC
Real-time soil gas vs. indoor air pressure differential	August 2010-present	Differential pressure presssure sensors connected to data logger system; reading every 2 minutes	All sub-slab locations outside and beneath building founcation	Sensors are re-zeroed every day
Real-time soil temperature	August 2010-present	Soil temperaure sensors coonected to data logger system; reading every 2 minutes	Selected location outdoor C and indoor location 1 at multiple depths	N/A
Real-time soil mositure	August 2010-present	Soil mositure sensors connected to data logger system, reading every 10 minutes	Selected location outdoor #C and indoor location #1 at multiple depths	Data are checked against the data from soil samples
Real-time soil O_2 concetrations	August 2010-present	O_2 sensors connected to data logger; reading every 10 minutes	All soil gas locations at sub-slab, 3-ft below slab (BS) and 6-ft BS	O_2 sensor calibration
Real-time indoor air, outdoor Air and AC temperature	December 2010-present	Thermocouples connected to data logger; reading every 2 minutes	Multiple locations such as Indoor, garage, AC duct, attic outdoor	N/A
Weather station: wind speed and direction, barometric pressure, precipitation, humidity	August 2010-present	Collected by a on-site data logging weather station; reading every 10 minutes	Weather conditions at the site	Data are checked against local government weather records
Real-time indoor and outdoor air sampling chlorinated compound concentrations	November 2010-present	Collected by thermal desorption tube followed by desorption and analysis by Unity-GC-MS in ASU lab; 4-hour time-averaged indoor air sampling	Indoor air sampling in living room downstairs	Data are checked against data from different methods and standard QA/QC procudures such as blanks, calibrations, internal standards
	February 2010-present	Collected and analyzed on site suing HAPSITE unit provided by Hill Air Force Base; 2-hour time-averaged sampling	Indoor air sampling under the stairs	
Real-time soil gas sampling, indoor and outdoor air chlorinated compound concentrations	February 2010-present	Collected by SRI 10-stream auto-sampler onto thermal desorption tubes followed by desorption and analysis using on-site GC-TO-14-ECD; sampling every 5 hours from each selected location	Indoor air sampling in living room downstairs, outdoor air and selected soil gas samples	Data are checked against data from different methods
Real-time indoor air and soil gas SF_6 sampling (Not in the proposal)	December 2010-present	Collected by SRI 10-stream auto-sampler and analyzed by GC-PDD; sampling every 2 hours from each selected locations	SF_6 is released continously at 5 ml/min indoor. Sampling at selected soil gas locations, indoor air and outdoor air	A standard is run every 5 hours
Real-time indoor air radon sampling (Not in the proposal)	February 2010-present	Collected and anallyzed on site by Durridge radon detector; 2-hour time-averaged indoor air sampling	Sampling indoor air downstairs	Instrument calibrated every 6 months
Real-time groundwater fluctuation	November 2010-present	In Situ Solinst level-logger; sampling every 12 hours	Sampling at GW3 at three depths	N/A
Monthly on-site soil gas SF_6, radon and chlorianted compounds, dissolved chlorianted compounds in groundwater, groundwater table level	August 2010-present* *SF_6 started in December 2010, Radon started in February 2011	Soil gas samples collected using lung-sampler and tedlar bags, then analyzed on site using GC-TO-14-DELCD, GC-DELCD, GC-PDD; groundwater collected and preserved in 40-ml vials then transported back to ASU lab for analysis using GC-DELCD; water level data collected using Solinst water lever sounder; soil gas radon analyzed by Durridge radon detector; sampling every month	All available soil gas and groundwater locations	Data are checked using blanks, duplicates, replicates trip blanks, sets of calibrations ect.
In situ effective diffusion coefficients	July 2011-present	Helium detector; sampling every month	All available soil gas sampling points	helium detector calibrated, duplicates, replicates

Modeling Studies

The Abreu and Johnson three-dimensional model (2005a, 2005b) was modified by Luo (2009) to incorporate asymmetrical surface pressure distributions resulting when wind blows against a building and also to utilize real-time weather data as an input. These changes were necessary to predict the high-frequency indoor-outdoor pressure differential changes with time that we have observed at our field sites. For this project, the model has been further modified to allow use of measured indoor-outdoor temperature difference data as an input to calculating indoor-outdoor pressure differentials with time. The numerical model is being used to identify combinations of site conditions (e.g., soil property distributions, foundation cracks, dynamic pressure fluctuations) that lead to significant spatial variability in sub-slab soil gas and temporal variability in indoor air concentrations.

Transient simulations using site-specific inputs, such as wind speed, barometric pressure, and indoor-outdoor temperature difference are currently running on processors in ASU's high-performance computing center. These computations are very processor time intensive, to the point that they run at close to real time or slower (e.g., it might require an hour or more of computing time to simulate an hour of real time).

Results and Discussion

Through the first 18 months years of this study a large quantity of data was generated and the priority has been to maximize the data collection and ensure data quality. As a result, only a simple analysis of the data has been conducted to date and more in-depth analyses will be conducted in the next year. Key results are presented below.

Indoor Air Concentration Changes with Time

Indoor air concentrations have been monitored since about February 2010. The data collected through December 2011 for trichloroethylene (TCE) are presented in Figure 4. Between February 2010 and November 2010, the house was being instrumented and it was used in late summer/fall 2010 by investigators of other SERDP/ESTCP projects, occasionally under manipulated building conditions. Those periods are indicated as "IST Studies" and "GSI Study" in Figure 4. Since November 2010, indoor air has been monitored under "natural conditions", which means that the air conditioner and heating mechanical systems were operated in the summer and winter, respectively, at set-points typical of residential homes. Two indoor air sampling and analysis methods have been used: active sampling on thermal desorption tubes followed by thermal desorption and analysis by gas chromatography - mass spectrometry (GC-MS), and sampling and analysis using HAPSITE (Inficon) portable GC-MS units provided by Hill AFB; these data are labeled "TD Tube Data" and "Hapsite data", respectively in Figure 4. Prior to November 2010, indoor air samples were collected and analyzed using only the HAPSITE unit. The concentrations obtained by the two different sampling and analysis methods are in reasonably good quantitative agreement when concentrations are above the detection limits for both methods.

Figure 5 presents expanded views of time periods in Summer 2010 and Fall 2011 to provide better insight to the types of observed changes with time. Other chemicals are also monitored, including: PCE, 1,1 DCE, cis-DCE, trans-DCE, vinyl chloride, 1,1,1-TCE, 1,1,2-TCA, 1,1-DCA, 1,2-DCA. Of these, TCE and 1,1-DCE are the most prevalent and behave similarly, so only the TCE data are presented here.

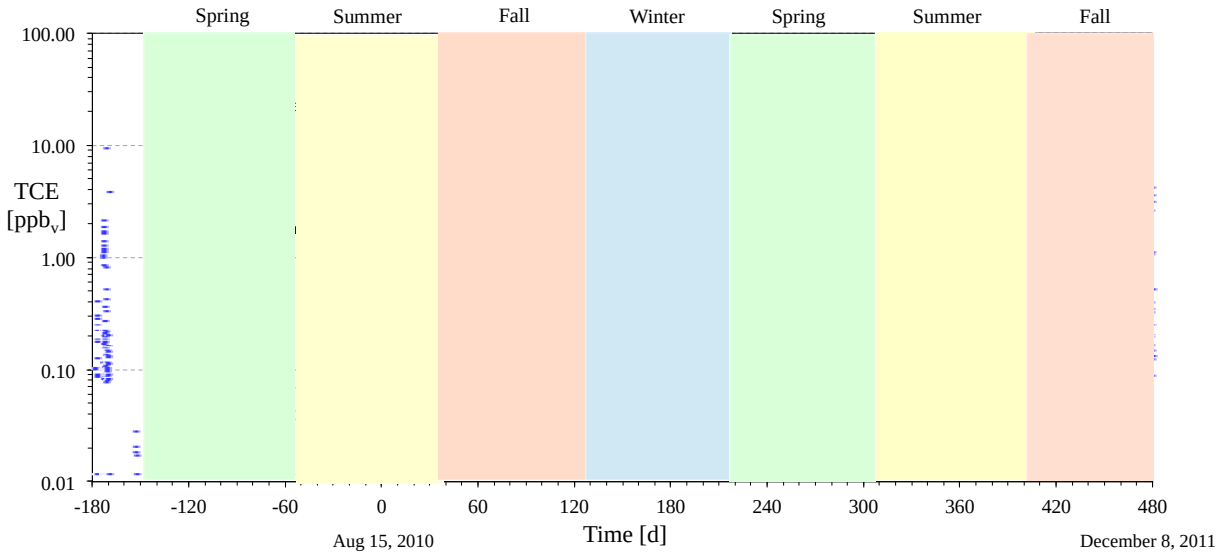


Figure 4. Indoor air monitoring data, with color blocks denoting seasons.

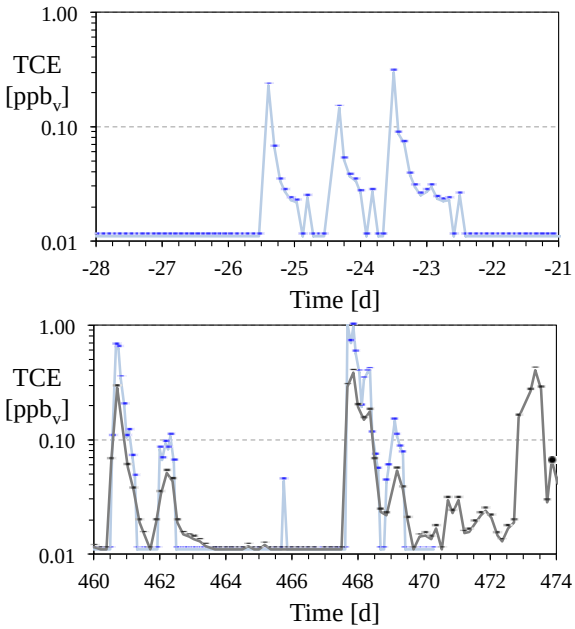


Figure 5. Expanded views of temporal indoor air concentration behavior in Summer 2010 and Fall 2011.

Key features of the data presented in Figures 4 and 5 include the following:

- Indoor air TCE concentrations vary irregularly with time by two to three orders-of-magnitude, ranging from non-detect levels (about 0.01 – 0.05 ppb_v, depending on the GC/MS sensitivity at the time of analysis) to over 10 ppb_v.
- There are periods ranging from days to weeks, when indoor air concentrations are mostly at or below non-detect levels, but occasionally increase to about 0.1 ppb_v levels for a few hours.
- There are periods ranging from days to weeks, when indoor air concentrations are well-above non-detect levels (even >0.1 ppb_v) and occasionally decrease back to non-detect levels.
- The most intense active time periods have been the fall and winter months and the less intensive vapor intrusion time period spans the spring and summer months.
- For reference, 0.08 ppb_v corresponds to approximately a 10^{-6} carcinogenic risk level as calculated by USEPA's VISL calculator (November 2011).

This is the first time that high temporal-resolution indoor air sampling has been conducted for such an extended period of time and the temporal pattern is unlike anything anticipated by guidance for vapor intrusion pathway assessment. It is not known if this behavior is representative of other houses, but at least for this one, it is clear that conventional point-in-time sampling approaches would likely be inadequate to characterize short- and long-term indoor air impacts. To restate this in another way, point-in-time sampling might lead to either underestimation or overestimation of indoor air impacts and their associated exposures and risks, depending on the particular date that was chosen for sampling.

The next sections present concentration changes with time along the vapor migration pathway, beginning with groundwater concentrations and then moving up to deep soil gas and shallow soil gas. Review of these provides insight to the causes of the temporal behavior observed in Figure 4.

Groundwater Concentration Changes with Time and Depth to Groundwater

Figure 6 presents groundwater TCE concentration changes with time for the shallowest groundwater samples collected beneath the foundation. Also plotted on this graph are groundwater table elevations (referenced to the sub-slab with an assigned relative elevation of 100 ft).

The important features here are that the dissolved concentration data mostly range between about 10 – 40 µg/L, or by factors of about 0.5 to 2 below and above the mean value, respectively. During this time, the groundwater table elevation change is about one foot.

As the temporal changes in groundwater concentrations are much less than the two to three orders of magnitude of variation in indoor air concentrations with time, it is reasonable to conclude that the changes in groundwater concentrations are unlikely to be the main factor in the observed indoor air concentration changes with time.

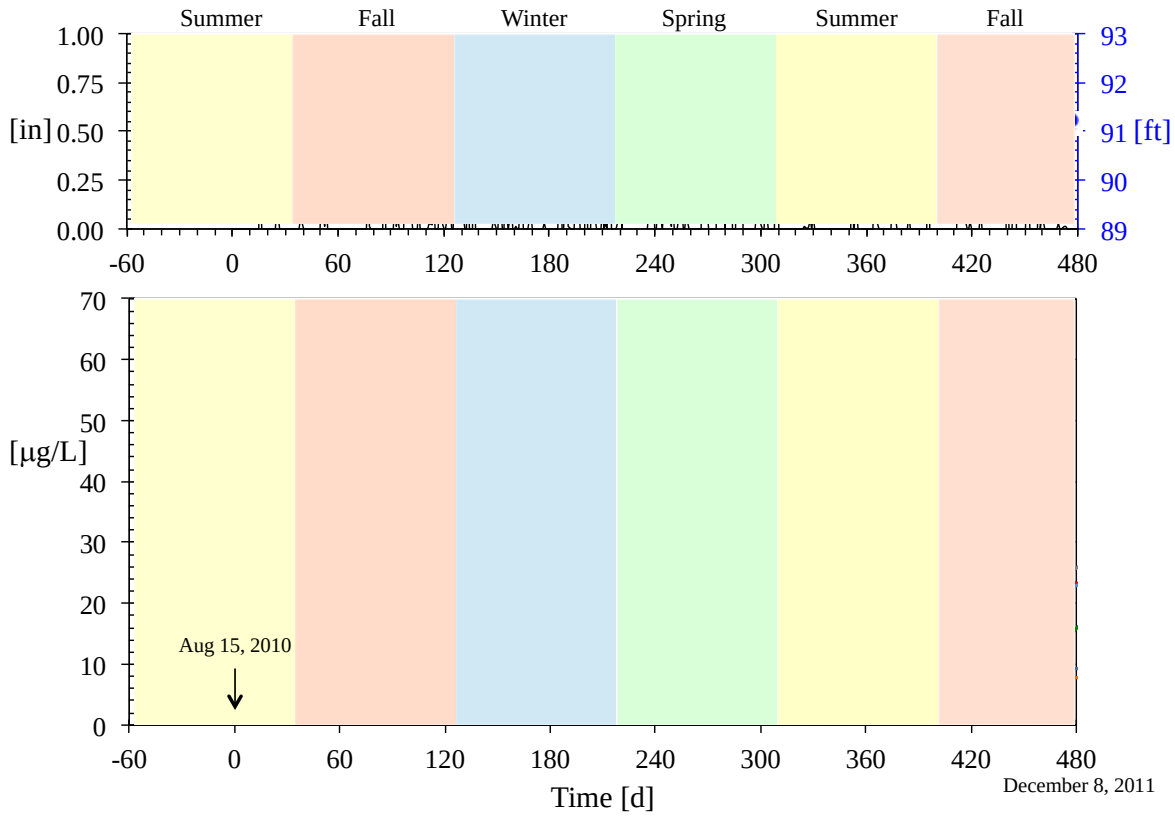


Figure 6. TCE concentration changes with time for the shallowest groundwater samples collected beneath the foundation, and groundwater elevation and precipitation vs. time (note: the foundation is assigned a reference elevation of 100 ft).

Soil Gas Contour Plots

Soil gas TCE concentration snapshots are presented below as contour plots for six of the thirteen sampling events and for three different depths moving upward toward the building from impacted groundwater: 6 ft below the slab (Figure 7), 3 ft below the slab (Figure 8), and sub-slab depths (Figure 9). Both temporal and spatial variability are observed in these figures. The deepest sampling depth contours exhibit concentration distribution contour shapes showing declining concentrations generally from north to south, as expected for a site with a sloping ground surface and decreasing depth to groundwater from north to south. For reference, the vapor concentration predicted to be in equilibrium with 20 µg/L TCE in water is about 1500 ppb_v, which is within about an order of magnitude of the 6-ft concentrations. The intermediate 3-ft depth partially reflects that spatial pattern, but it also consistently has about a 10X decrease in concentrations in moving from west to east beneath the slab (left to right across the figures). At the sub-slab depth, the spatial distribution varies significantly from event to event, with no clear or consistent spatial pattern as is observed at the deeper depths.

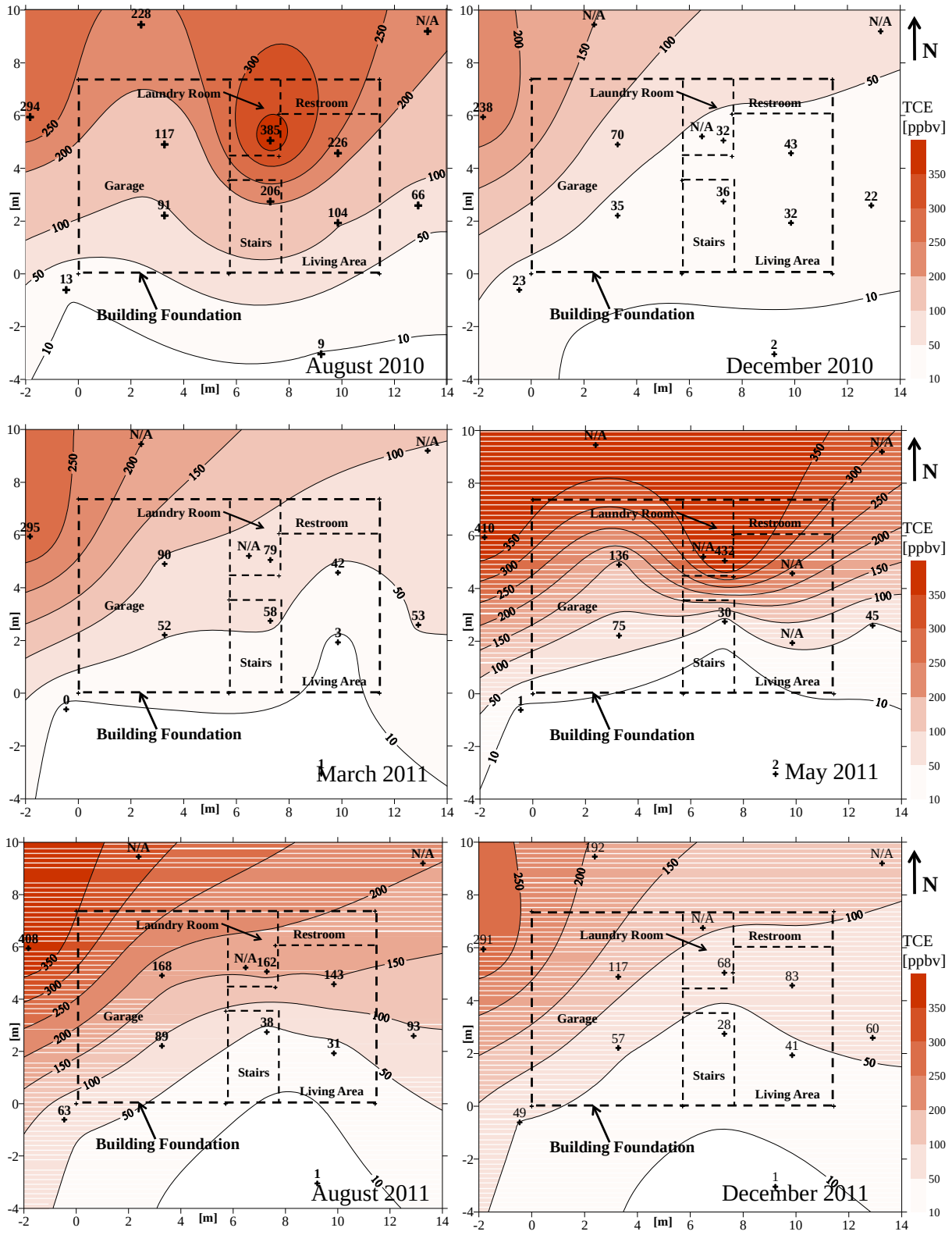


Figure 7. Sample TCE soil gas contours [ppb_v] at 6-ft below the foundation for six of the thirteen snapshot sampling events.

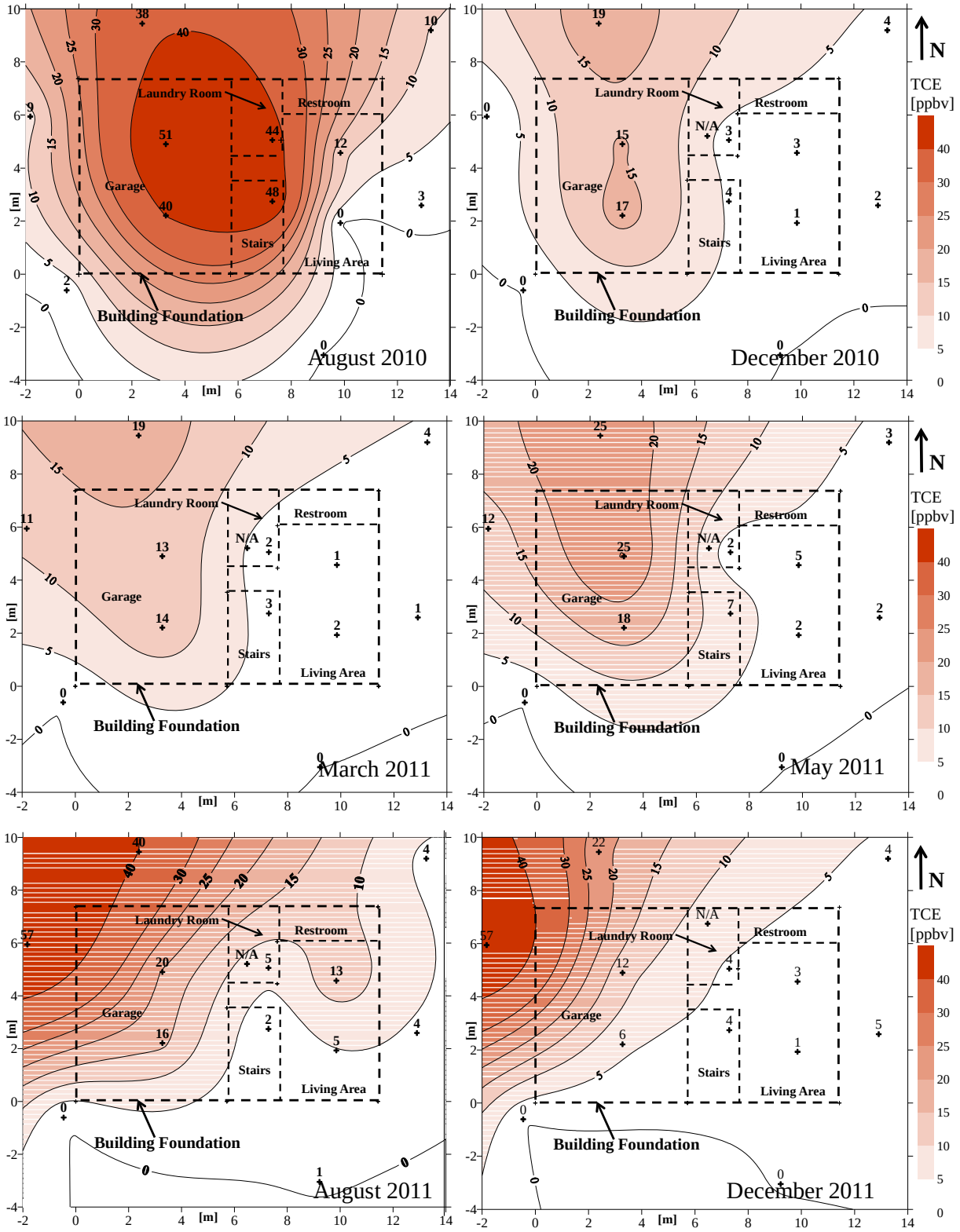


Figure 8. Sample TCE soil gas contours [ppb_v] at 3-ft below the foundation for six of the thirteen snapshot sampling events.

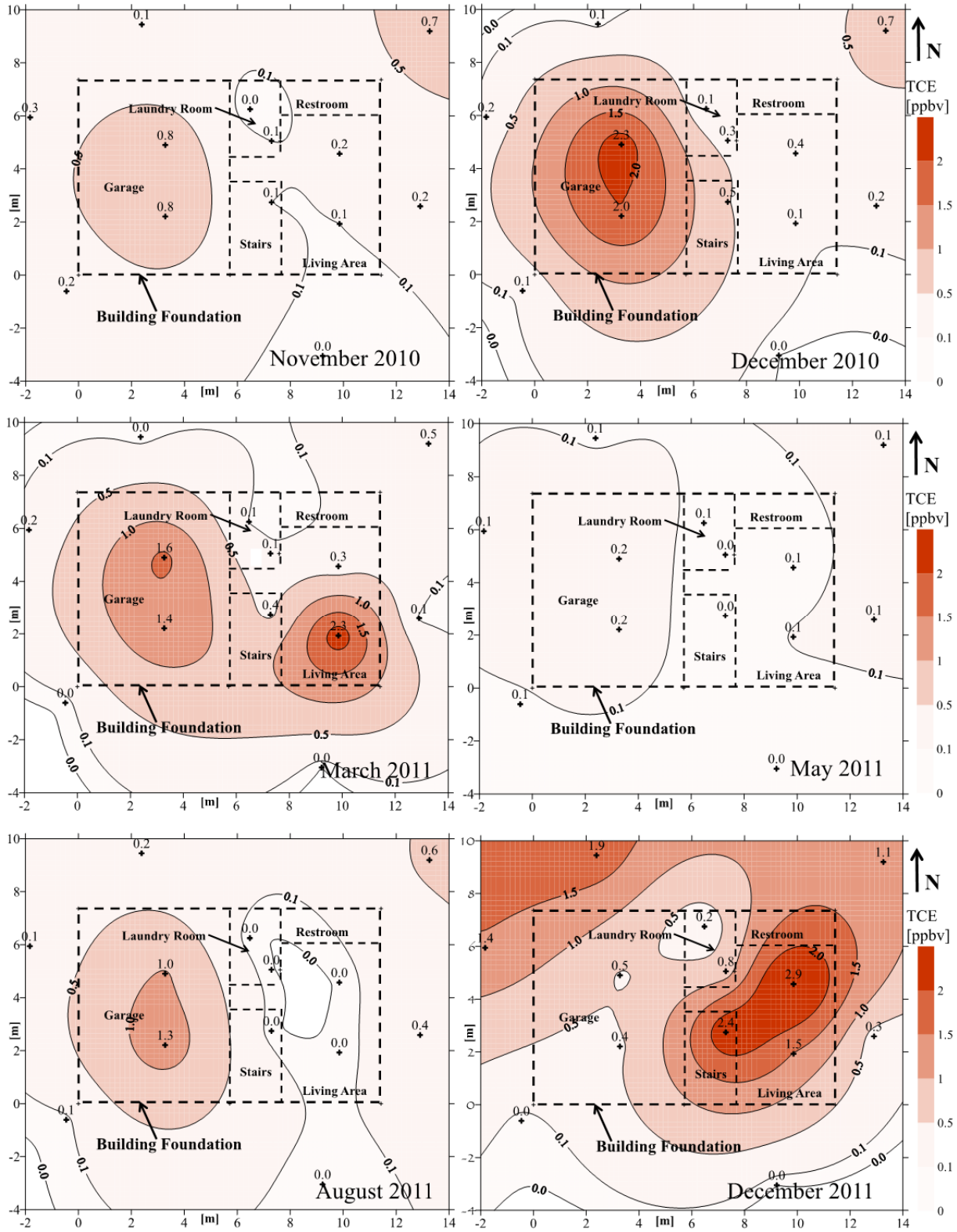


Figure 9. Sample TCE soil gas contours [ppb_v] at sub-slab depth for six of the thirteen snapshot sampling events.

Soil Gas Concentration Changes with Time

Soil gas concentrations were monitored in real-time at two depths (sub-slab and 3-ft below slab) at three locations (1, 2, and 6) between day 280 and day 480 using an auto-sampling GC-ECD method (different from the GC-DELCD method used for the snapshot contoured data above). These locations were chosen based on the snapshot data shown above in the contour plots. Sample data at Location 1 and Location 6 are shown below in Figure 10. The data gaps are a result of analytical instrument remote control issues. As can be seen, the soil gas concentrations at Location 1 generally remain within about 50% of the average concentration over the 200 day monitoring period, while the soil gas concentrations at Location 6 vary by at least an order of magnitude over the same period of time, and this is consistent with the variability observed in the soil gas sampling snapshots presented above in Figures 8 and 9.

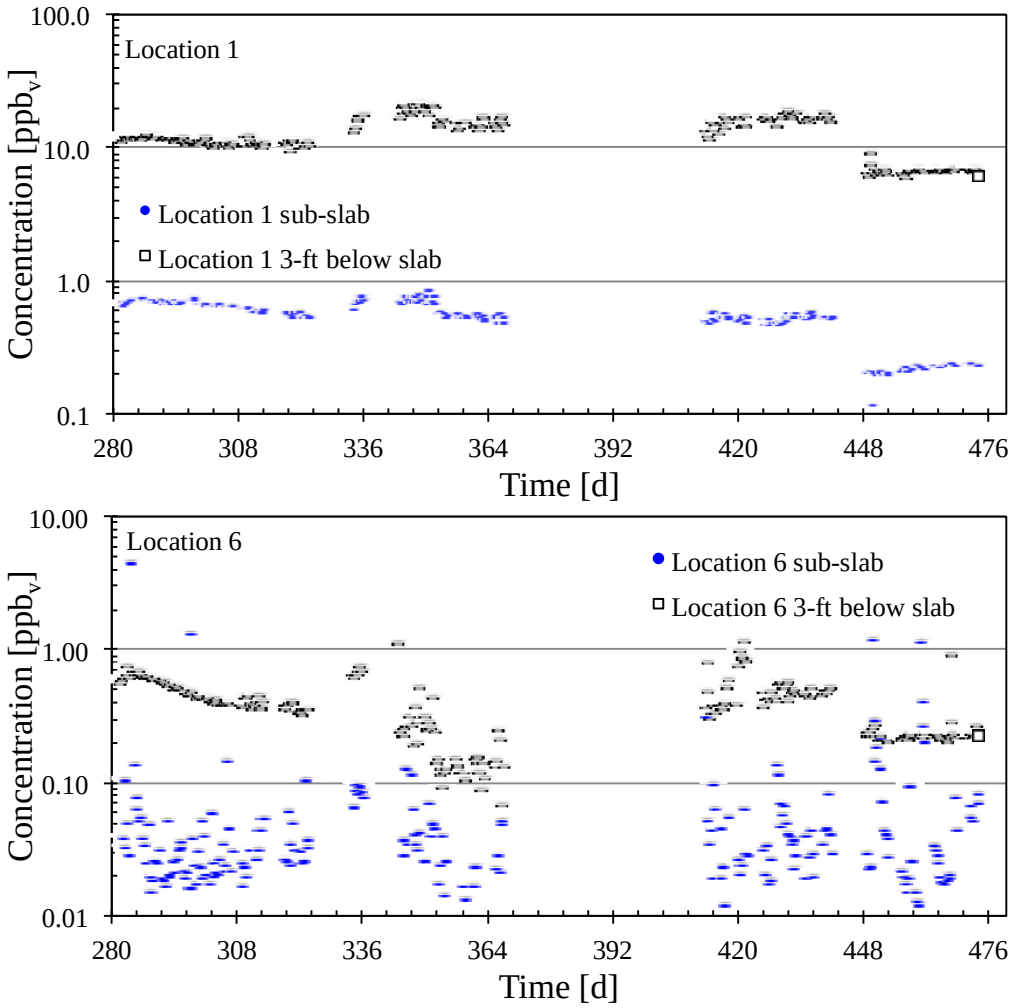


Figure 10. TCE soil gas concentrations vs. time at two depths and two locations.

Real-Time Monitoring of Indoor Air Radon Concentrations with Time

While not part of the original scope of work for this project, indoor and subsurface radon monitoring were added to the activities. This was done because some have proposed the use of radon sampling as a diagnostic tool for assessing vapor intrusion. This study provides what may be the first opportunity to evaluate that. In particular, there is interest in determining if:

- Indoor radon concentrations can be used as a qualitative indicator that vapor intrusion is occurring, and

- Indoor radon concentrations in combination with radon soil gas concentrations can be used to qualitatively estimate potential indoor air impacts from other chemicals.

Figure 11 presents real-time indoor air radon monitoring data vs. time compared with TCE indoor air concentrations. In both cases, the real-time data sets have been transformed to daily-averaged values to simplify the visual presentation. The overall temporal trends are similar for both TCE and radon, but the magnitudes of changes with time are much different. While the TCE concentrations vary over about two orders of magnitude, the radon concentration changes only by about a factor of two to three. That is in part a reflection of the differences in the dynamic detection ranges of the two monitoring methods. For example, the radon detector signal does not decrease below about 0.2 – 0.5 pCi/L even under clean air conditions and, per manufacturer's instructions, 0.5 pCi/L is a lower confidence bound for quantification with this radon detector. Thus the radon behavior qualitatively reflects the TCE indoor air behavior when TCE concentrations exceed about 0.2 ppb_v.

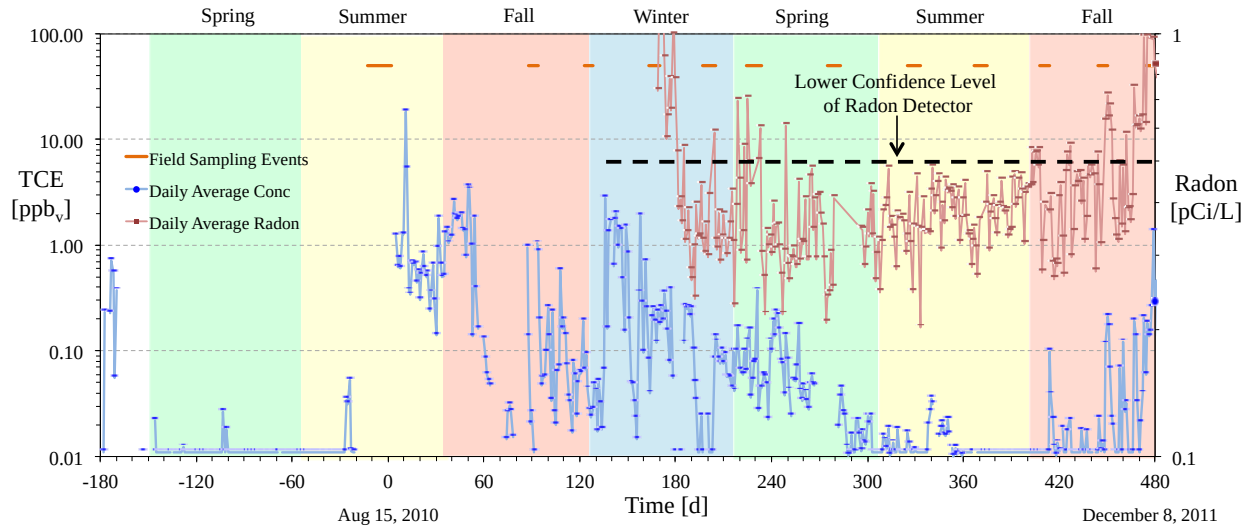


Figure 11. TCE and radon indoor air concentrations vs. time.

Radon Concentrations in Soil Gas

Radon concentrations are quantified during the soil gas sampling snapshot events. A review of the data suggests that the radon distribution is relatively uniform spatially and consistent with time at 3-ft and 6-ft below slab depths, and is most variable in time and space at the sub-slab depth. Therefore, only December 2011 snapshot data are presented in Figure 12 for the 6-ft and 3-ft below slab depths and two sample plots (September 2011 and December 2011) are shown for the sub-slab depth. The greatest variability in concentration with time occurs beneath the east side of the slab (right-hand side of the contour plots). It can be seen that concentrations vary by an order of magnitude at the two eastern sampling locations between the September and December 2011 sampling events.

While the TCE soil gas data presented above also showed greatest temporal variability under the eastern portion of the foundation, it should be noted that the TCE and radon soil gas distributions are quite different, reflecting the differences in their sources (groundwater at some depth vs. radioactive decay throughout the soil, respectively).

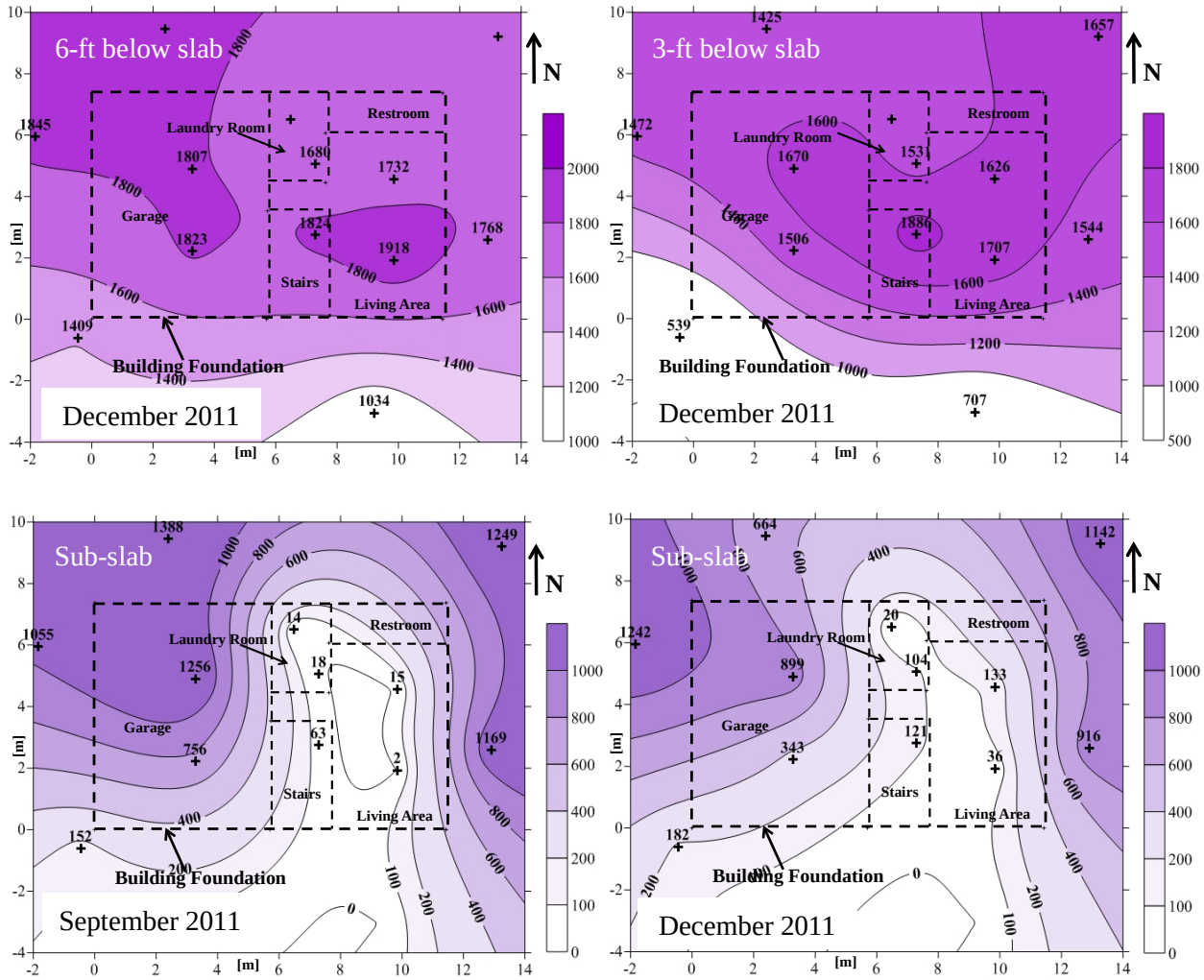


Figure 12. Radon soil gas concentration contours [pCi/L].

Real-time Monitoring of SF_6 in Indoor Air

Sulfur hexafluoride (SF_6) has been continuously released into indoor air at a constant rate of 5 ml/min since December 2010. This permits monitoring of changes in indoor air exchange rate, the exchange of indoor air and soil gas, and changes in indoor air concentrations expected with steady-emitting indoor air sources.

Indoor air SF_6 data are presented below in Figure 13. Using the short-term transient response at the start of SF_6 release and well-mixed mass balance equations, the effective building air exchange volume is calculated to be about about 400 m^3 for this house. The data in Figure 13 indicate the following:

- The building exchange rate is greatest in winter months and lowest in the spring/summer transition (decreasing SF_6 concentrations correspond to increasing exchange rates). Within a given day, the air exchange rate appears to vary by 2X to 4X in a fairly repeatable pattern. We are currently evaluating the late spring/early summer 2011 data to assess if detector non-linearity is contributing to the apparent 5X increase in SF_6 concentrations in comparison with winter months.

- Indoor air concentrations resulting from steady indoor sources might vary by as much as 2X daily and up to 5X seasonally.

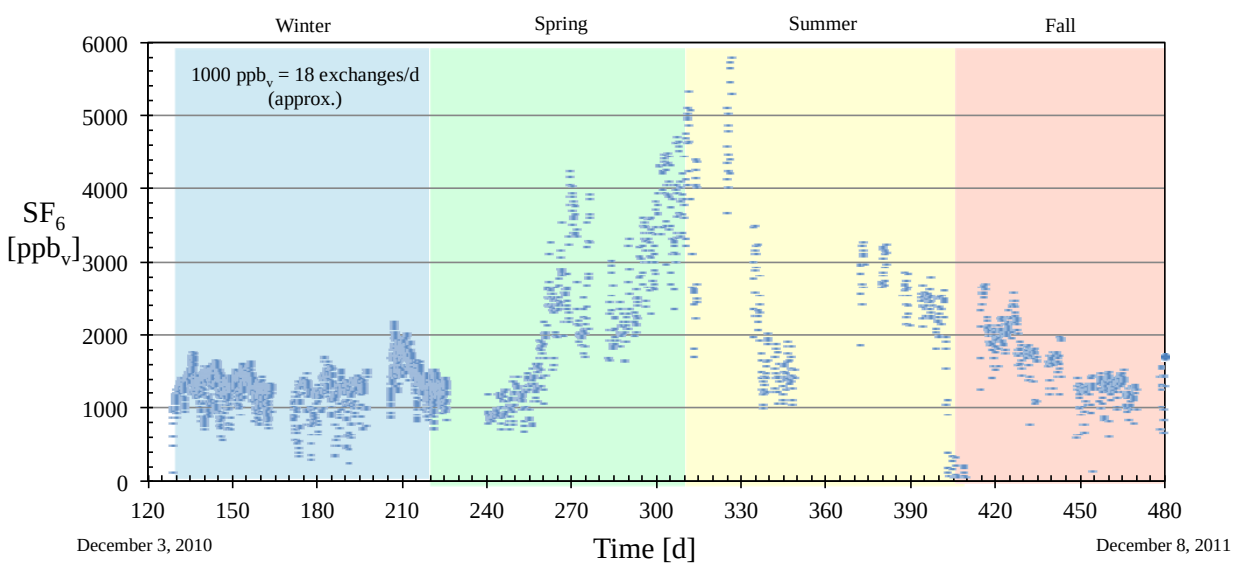


Figure 13. SF_6 in indoor air with a constant 5 mL/min release rate. For reference, 1000 ppb_v corresponds to about 18 indoor air exchanges per day.

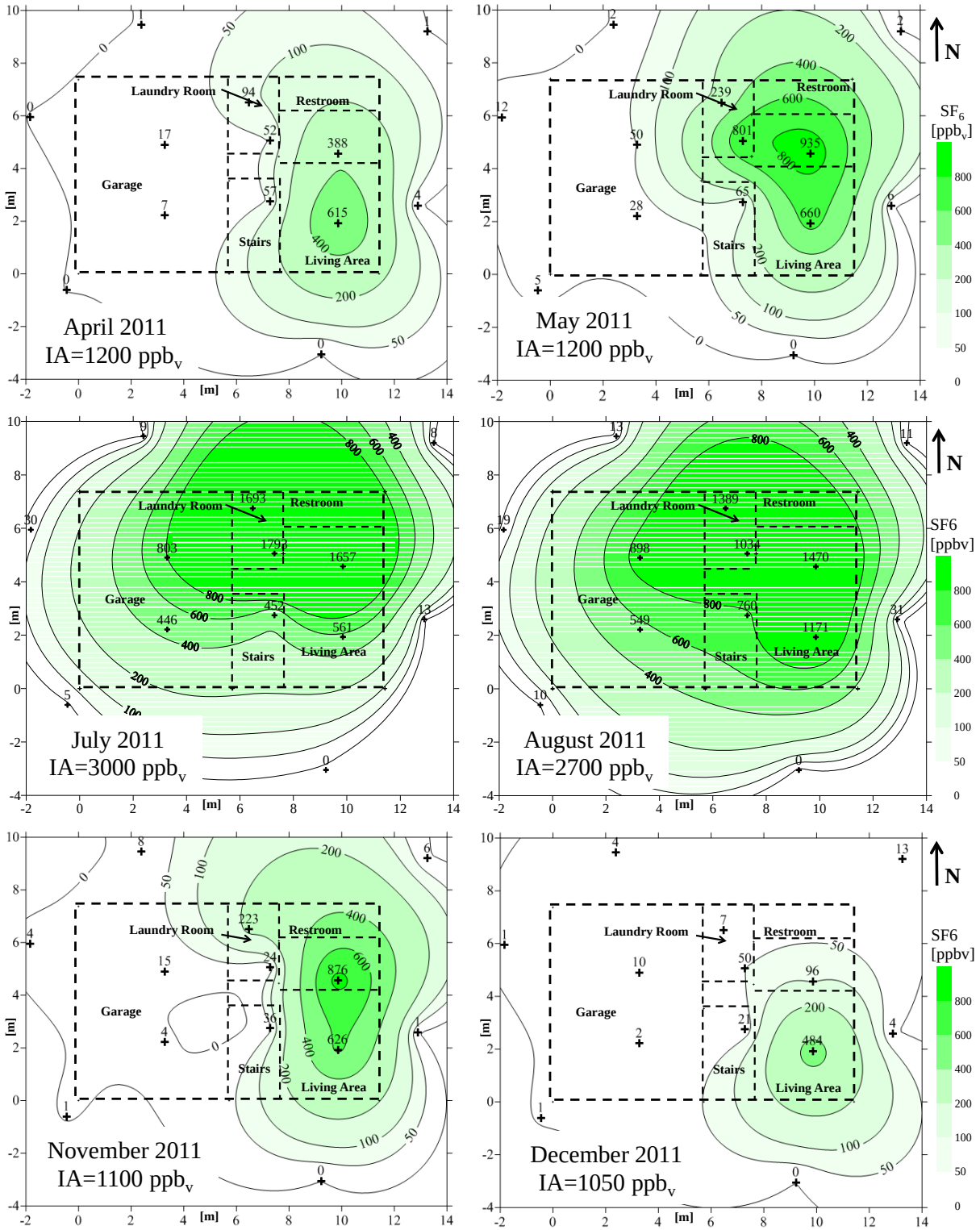


Figure 14. SF_6 in sub-slab soil gas resulting from a constant 5 mL/min indoor release rate. For reference, the indoor air concentration (IA) on the sampling date is also shown on the figures.

Soil Gas Monitoring of SF_6

The appearance of SF_6 in soil gas resulting from indoor air release has been observed. SF_6 concentrations in sub-slab soil gas for six sampling events are shown in Figure 14. These results are significant because it is often assumed during vapor intrusion pathway assessment that the presence of a contaminant in both indoor air and soil gas is evidence of subsurface vapor intrusion. These data show that the presence of a contaminant in both indoor air and soil gas can also result from indoor air sources, and that the resulting subsurface vapor distribution can change with time.

Conclusions to Date

The following are key accomplishments and conclusions for the first 1.5 years of this research project:

- More than twenty months of high frequency real-time indoor air monitoring data have been collected and the results provide new insight to the temporal nature of vapor intrusion impacts to indoor air. It is not known if the behavior at the study house is representative of other homes, but the data show that indoor air concentrations resulting from a dissolved groundwater plume can vary with time by two to three orders of magnitude. The temporal behavior appears to be seasonal, with periods ranging from days to weeks when indoor air concentrations are mostly at or below non-detect levels, and with occasional increases to about 0.1 ppb_v for a few hours. There are also periods ranging from days to weeks when indoor air concentrations are well-above non-detect levels (even >0.1 ppb_v) and occasionally decrease back to non-detect levels. The most intense VI activity time periods have been the fall and winter months and the less intensive VI time period spans the spring and summer months.

- The practical implications of the indoor air monitoring data are that: (a) low concentration (10's of µg/L) dissolved plumes can cause indoor air impacts at levels of concern, and (b) conventional infrequent point-in-time sampling methods are unlikely to be capable of adequately characterizing indoor air impacts resulting from vapor intrusion.

- The monthly groundwater concentration monitoring conducted for more than 14 months shows groundwater elevation changes of about one foot, and groundwater concentration changes with time of only about 0.5X to 2X the long-term mean. This suggests that groundwater concentration changes are not the primary factor driving the indoor air temporal behavior.

- The monthly soil gas concentration monitoring conducted for more than 14 months shows deep (6-ft below slab) soil gas concentrations consistent with dissolved groundwater concentrations and with temporal variability comparable to groundwater concentration changes. Sub-slab soil gas contour plots show high spatial and temporal variability (at least an order of magnitude), with greatest variability beneath the eastern

side of the foundation. The intermediate depth (3-ft below slab) data reflect surface influences as well, although not to the extent evident in the sub-slab soil gas data.

- High-frequency real-time soil gas sampling results confirm that deeper soil gas concentrations are more stable with time than near-surface or sub-slab concentrations.

- The practical implication of the groundwater and soil gas data is that near-source concentrations are likely to more stable with time and space, and therefore might be more reliable indicators of vapor intrusion potential than near-surface or sub-slab sampling.

- High frequency (2-h interval) indoor air radon concentrations have been monitored for about one year and soil gas radon concentrations snapshots have been collected monthly for about a year. The overall temporal trends are similar for both TCE and radon, but the magnitudes of changes with time are much different. While the TCE concentrations vary over about two orders of magnitude, the radon concentration changes only by about a factor of two to three. That is in part a reflection of the differences in the dynamic detection ranges of the two monitoring methods. For example, the radon detector signal does not decrease below about 0.2 – 0.5 pCi/L even under clean air conditions and, per manufacturer's instructions, 0.5 pCi/L is a lower confidence bound for quantification with this radon detector. Thus the radon behavior qualitatively reflects the TCE indoor air behavior when TCE concentrations exceed about 0.2 ppb_v.

- The radon distribution in soil gas is relatively uniform spatially and consistent with time at 3-ft and 6-ft below slab depths, and is most variable in time and space at the sub-slab depth. The greatest variability in concentration with time occurs beneath the east side of the slab, which is also the area and depth of greatest variability for TCE concentrations.

- The practical implications of the indoor and soil gas radon data are that: a) radon might be useful as a qualitative indicator of the occurrence of vapor intrusion, but only if the detector is sufficiently sensitive to detect the presence of radon at levels that are of interest; and b) quantitative relationships derived between indoor and subsurface concentration data for radon should not be used to estimate indoor air concentrations of other chemicals using their subsurface concentrations.

- The continuous release of SF_6 to indoor air has provided valuable insight to indoor air exchange rate changes with time and possible impacts of indoor air sources: a) temporal variations in indoor air exchange rate might be as much as 2X daily and 5X seasonally; b) indoor air sources will have indoor air temporal signatures that reflect the temporal variations in indoor air and so can be expected to vary by 2X to 5X; and c) indoor air sources can result in subsurface soil gas clouds.

- The practical implications of the continuous SF_6 release results are that: a) variations of 2X to 5X indoor air concentrations should be expected even for steady-strength sources, whether the source is indoor or in the subsurface, and b) the presence of a chemical in soil gas and indoor air should not be interpreted to confirm a complete vapor intrusion pathway, unless other data support that interpretation.

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