

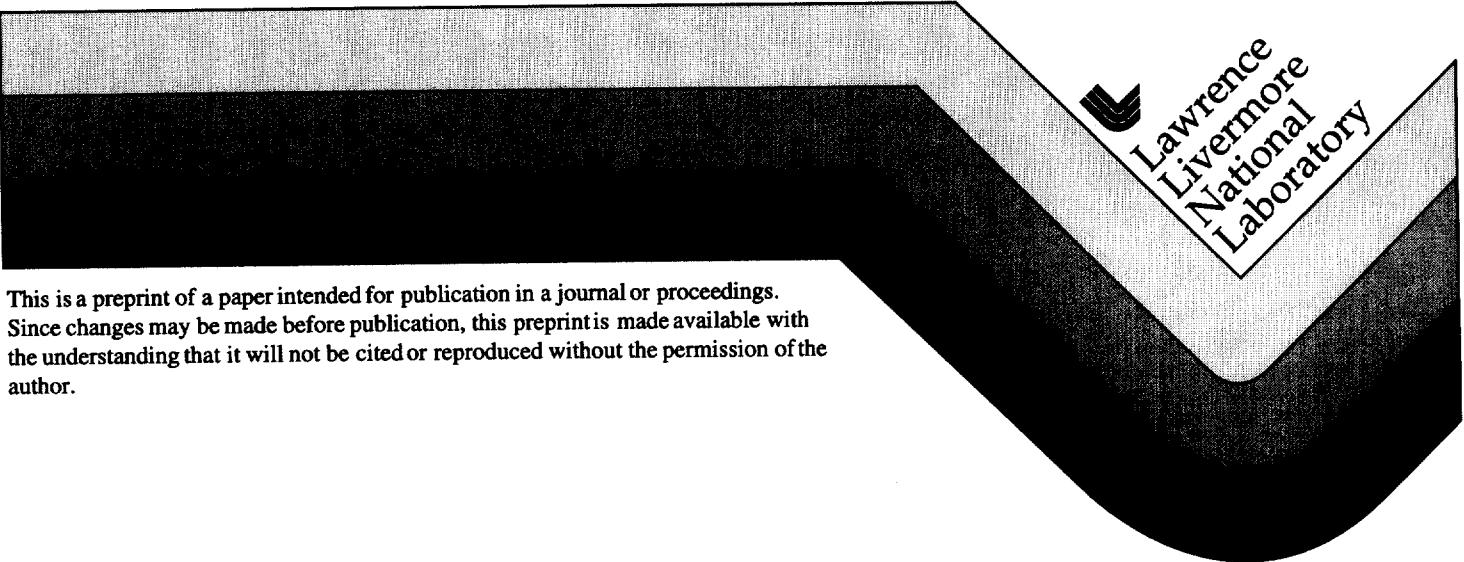
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Case Study Comparisons of Vapor Inhalation Risk Estimates: ASTM RBCA Model Predictions Vs Site Specific Soil Vapor Data

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CASE STUDY COMPARISONS OF VAPOR INHALATION RISK ESTIMATES: ASTM RBCA MODEL PREDICTIONS VS SITE SPECIFIC SOIL VAPOR DATA

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ABSTRACT

The American Society for Testing and Materials (ASTM) Standard E-1739, Risk-Based Corrective Action Applied at Petroleum Release Sites (RBCA), offers a streamlined methodology for selecting and implementing cost-effective corrective action for petroleum hydrocarbon release sites. ASTM is also currently developing the Standard Guide for Risk Based Corrective Action which extends the RBCA process to include a wide range of chemicals of concern. Comparing the results derived from the RBCA vapor transport models with field data has underscored the extremely conservative nature of the RBCA inhalation pathway models. Two case studies are described in this paper which compare exposure point concentrations and human health risk estimated from the RBCA vapor transport models and actual measurements of soil vapor concentrations and soil vapor flux.

The first case study involves a residential property adjacent to a leaking underground storage tank site. The excess carcinogenic human health risk for benzene using surface vapor flux and soil vapor profile data ranged from 5.3×10^{-8} to 7.2×10^{-6} , whereas the benzene risk estimated from the RBCA models using ground water and soil samples ranged from 1.4×10^{-3} to 1.6×10^{-3} . The risk difference is attributable to an exponential decrease with distance from the ground water table in hydrocarbon concentrations in vadose zone soil vapor. The RBCA models do not predict this soil vapor concentration profile. Hydrocarbon biodegradation in the vadose zone was most likely responsible for the concentration decreases.

The second case study involves chlorinated volatile organic compound (VOC) contamination in soil and groundwater at a Federal Superfund site. Data was collected using the emission isolation flux

chamber methodology and direct soil vapor measurements. Results for trichloroethylene soil vapor flux and soil vapor concentration profiles in the vadose zone indicate large differences between transport rates estimated using RBCA models and those measured in the field.

This paper focuses upon the RBCA treatment of critical vapor transport mechanisms for petroleum hydrocarbon and VOC contamination. The results of the comparison underscore the conservative nature of the RBCA vapor inhalation pathway models, and the importance of collecting site specific vapor data near potential vapor inhalation receptors.

METHODOLOGY

ASTM Modeling Methodology

Exposure point concentration and human health risk estimates for the vapor inhalation pathway were made using models presented in the American Society for Testing and Materials (ASTM) Standard E-1739, *Risk-Based Corrective Action Applied at Petroleum Release Sites* (RBCA) (ASTM, 1996). Estimates are based upon site-specific soil and groundwater concentration and results from soil vapor and flux chamber measurements.

The RBCA models assume simple equilibrium concentrations between the groundwater, soil and soil vapor phases. Transport in the soil vapor phase is estimated assuming first order diffusion from the contaminant source to the ground surface, where the hydrocarbon concentration is assumed to be zero. The estimated soil vapor flux is, therefore, determined by the concentration gradient from the source area to the soil surface and the effective diffusivity in the vadose zone. The effective diffusivity is estimated based upon the total and water filled porosity.

To estimate exposure-point concentrations of VOCs in air, the RBCA guidance applies a simple box model to estimated values of VOC soil vapor flux. The box model used to estimate VOC exposure point concentrations in outdoor air is the same as that recommended by U.S. EPA Superfund guidance (USEPA, 1992) and has the form:

$$C_{\text{outdoor}} = \frac{F \cdot L}{U_w \cdot H_m},$$

where

C_{outdoor} = VOC concentration resulting from the estimated or measured soil vapor flux, $\mu\text{g}/\text{m}^3$

F = Estimated or measured VOC soil vapor flux, $\mu\text{g}/(\text{m}^2 \cdot \text{sec})$,

L = Maximum downwind length of the VOC emission source (site specific), m,

U_w = Average wind speed within the mixing zone, 2.25 m/sec (ASTM default parameter), and

H_m = Ambient air mixing zone height, 2 m (ASTM default parameter).

To simplify the analysis of site specific data, the concentration in indoor air is estimated by conservatively assuming the estimated or measured surface vapor flux measured near the building foundation is present beneath the building with no slab attenuation (as if the building had a dirt floor). This approach is considerably more conservative than the Tier 1 models recommended in the RBCA Guidance (ASTM, 1996) which assumes a slab attenuation. The ASTM indoor air box model used for this analysis therefore has the form:

$$C_{\text{indoor}} = \frac{F_{\text{max}}}{ER_{\text{air-indoor}} \times L_b}$$

where

C_{indoor} = VOC concentration resulting from the estimated or measured soil vapor flux, $\mu\text{g}/\text{m}^3$

F = Estimated or measured VOC soil vapor flux, $\mu\text{g}/(\text{m}^2 \cdot \text{sec})$,

$ER_{\text{air-indoor}}$ = Enclosed space air exchange rate (sec^{-1})

L_b = Enclosed space volume/infiltration area ratio, m.

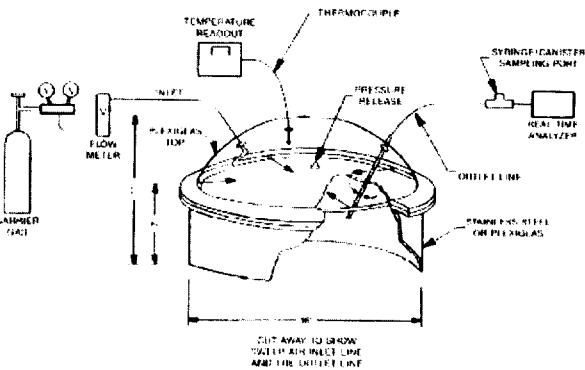
Once exposure point concentrations have been estimated, human health risk estimates for the vapor inhalation pathway are estimated based upon ASTM default inhalation dose parameters.

Although the ASTM models are simple to apply, they are also very conservative. As a result, the

models are applied as a screening method only. Actual air concentrations corresponding to measured VOC soil vapor flux emissions are expected to be lower than those estimated by application of this model.

VOC Surface Vapor Flux Measurements

Surface vapor flux is a measurement of the emission rate of contaminants of concern at the ground surface. The emission isolation flux chamber methodology used is based on U.S. EPA guidance and is applicable to the measurement of air emission rates at the ground surface from sites where contaminants have been released to the surface or subsurface (USEPA, 1986). The emission isolation flux chamber technique is listed as the preferred testing technique for the direct measurement of VOC vapor emission by the U.S. EPA in the *Air/Superfund Technical Guidance Series* (USEPA, 1990).



The emission isolation flux chamber system is composed of three parts: the chamber, the sweep air controller, and the sampling system. The flux chamber contains a stainless steel sweep air inlet tube with perforations which create air mixing, and ports for sample collection, pressure release, and a thermocouple to measure the chamber temperature. The sweep air controller includes an ultra-pure sweep air pressurized gas canister, a pressure regulator and a rotometer to measure the sweep airflow rate. The sampling system includes clean Teflon tubing, an evacuated 6-liter SUMMA canister, a sampling pump and a rotometer to measure the exhaust airflow rate. The pressure regulator, sampling pump and two rotometers are used to control air flow in and out of the chamber to maintain a negligible pressure differential between the chamber and the sub-surface soil.

The emission isolation flux chamber is placed on the ground surface, and hydrocarbon surface vapor flux emissions enter the open bottom of the chamber. Clean dry sweep air is added into the chamber at a metered rate. Within the chamber the sweep air mixes with emitted hydrocarbon vapors. When the concentration of the hydrocarbon surface vapor flux

emissions and the sweep air reaches equilibrium, a sample is collected in a 6 liter SUMMA canister for analysis. The measured surface vapor flux (emission/area-time) is then calculated from the petroleum hydrocarbon vapor concentration using the following formula:

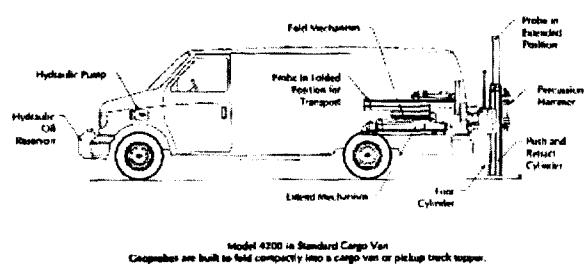
$$F_{\text{meas}} = \frac{Q_{\text{sweep}} \times C_{\text{summa}}}{A_{\text{chamber}}} \quad (1)$$

where

F_{meas} = Measured hydrocarbon soil flux, $\mu\text{g}/(\text{m}^2 \cdot \text{sec})$,
 Q_{sweep} = Sweep flow rate, m^3/sec ,
 C_{SUMMA} = VOC vapor concentration in SUMMA canister sample, $\mu\text{g}/\text{m}^3$, and
 A_{chamber} = Surface area enclosed by the chamber, m^2 .

Soil Vapor Concentration Measurements

Soil vapor survey (SVS) samples are typically collected using GeoProbe direct-push soil vapor sampling equipment at multiple depths. This methodology is simple to apply where only relatively shallow soil vapor samples are required. In application where deeper soil vapor samples are needed (>20-30 ft below ground surface), such as applied in the second case study of this paper, a combination drill rig and direct push methodologies may be required. Typically, if the primary concern is estimating risk due to the vapor inhalation pathway, shallow soil vapor measurements (<15-ft bgs) are adequate.



Multiple soil vapor samples with depth are collected to help characterize the soil vapor gradient from the source of subsurface contamination to ground surface for correlation with the measured surface vapor flux. To the extent possible, sampling locations for the two case studies were selected to coincide with surface vapor flux sampling points. For petroleum hydrocarbon contamination sites, samples are collected in 1-liter SUMMA canisters for EPA Method TO-3 BTEX offsite analysis and in glass syringes for onsite analysis for oxygen, carbon dioxide and methane. For chlorinated hydrocarbon contamination sites, samples are collected in 6-liter SUMMA canisters for offsite EPA Method TO-14 VOC analysis.

During the soil vapor survey, ambient air samples are collected in the vicinity of the suspected subsurface contamination at breathing level with a flow controller set to collect an 8-hour integrated sample. Ambient air samples are collected using a 6-L SUMMA canister for the EPA Method TO-14 analysis. The ambient air sample provides a measure of the background air concentration of the chemicals of concern.

CASE STUDY 1: PETROLEUM HYDROCARBON CONTAMINATION SITE

VOC Surface Vapor Flux Results

The first case study involves a residential property adjacent to a leaking underground storage tank site. Petroleum hydrocarbons have been observed in ground water at this site, and are believed to be present in ground water beneath the building. Using the emission isolation flux chamber methodology, direct measurements of surface vapor flux were collected at six different locations near the base of the impacted building. The depth to the first water bearing zone at this site is approximately 10-ft.

The average benzene surface vapor flux measured was $4.6 \times 10^{-4} \mu\text{g}/(\text{m}^2 \cdot \text{sec})$. The benzene concentration measured in the field blank sample was 0.20 ppb_{v/v} (0.65 $\mu\text{g}/\text{m}^3$) resulting in a calculated flux of $3.0 \times 10^{-4} \mu\text{g}/(\text{m}^2 \cdot \text{sec})$. It is likely that detectable petroleum hydrocarbon concentrations in surface vapor flux samples are partly due to background concentrations of petroleum hydrocarbons in ambient air. It is common that even surface vapor flux measurements collected in urban areas with no known contamination will show similar surface vapor flux levels to those observed at this site due to contaminant concentrations in ambient air (DeVaull et al., 1994).

Eight-hr average concentrations for ambient air collected concurrent with soil vapor flux measurement activities contained $1.7 \mu\text{g}/\text{m}^3$ (0.53 ppb_{v/v}) benzene. This benzene concentration is typical for an urban air sample, particularly for one from near an operating service station. The average 1994 benzene concentration in Bay Area ambient air was 1.3 ppb_{v/v} (4.2 $\mu\text{g}/\text{m}^3$).

The average benzene surface vapor flux of $4.6 \times 10^{-4} \mu\text{g}/(\text{m}^2 \cdot \text{sec})$ was used to estimate the benzene concentrations in indoor air and associated human health risk using a subset of the RBCA guidance models. As described above, the concentration in indoor air is estimated by conservatively assuming the average benzene surface vapor flux measured near the building foundation is present beneath the building with no slab attenuation. Standard RBCA defaults

were assumed for indoor air exchange rates and inhalation dose parameters.

Based on these assumptions, the estimated concentration in indoor air is $0.82 \mu\text{g}/\text{m}^3$ (0.25 ppb_{vv}). The individual excess cancer risk associated with this concentration, using the Cal-EPA cancer slope factor for benzene of 0.1 kg-day/mg , is 7.2×10^{-6} . Due to the presence of background benzene concentrations in the emission isolation flux chamber samples, this provides an upper bound, screening level estimate of the human health risk associated with subsurface petroleum hydrocarbon contamination at this site.

Soil Vapor Survey Results

SVS samples were collected at six separate locations in the vicinity of the adjacent building at three depths (approximately 3, 6 and 9 ft). Because groundwater and soil vapor concentrations are expected to decrease exponentially with distance (horizontal) from the source area, rather than linearly, taking the average soil vapor concentration for each depth provides a conservative estimate of soil vapor concentrations beneath the building. Figure 1 displays a plot of the average measured petroleum hydrocarbon, oxygen and carbon dioxide concentrations with depth. The average benzene concentrations for each soil vapor sample depth are presented in Table 1.

Table 1 Average SVS benzene concentrations

Depth (ft)	Benzene Concentration ($\mu\text{g}/\text{m}^3$)
3	4.2
6	9.2
8-9	3,300

The average benzene concentration for soil vapor was used to estimate the indoor air concentrations and associated individual excess cancer risk using RBCA guidance models. Again, the indoor air concentration is estimated by conservatively applying the ASTM guidance models assuming no slab attenuation (dirt floor), no basement ventilation and perfect mixing with air within the residential living space above. Average site-specific values for bulk density and grain density used in these calculations were taken from the GeoProbe soil samples.

The estimated indoor air concentration based upon the measured benzene concentration at 8 ft is $0.84 \mu\text{g}/\text{m}^3$ (0.26 ppb_{vv}). The individual excess cancer risk associated with this concentration, using the Cal-EPA cancer slope factor of 0.1 kg-day/mg , is 7.4×10^{-6} . It is interesting to note the effect of the measured

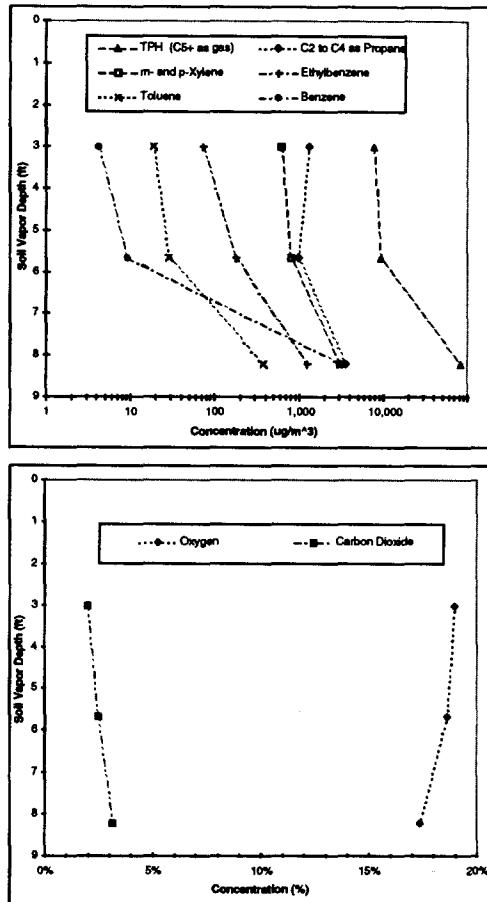


Figure 1: Average SVS petroleum hydrocarbon, oxygen and carbon dioxide concentrations with depth below ground surface.

vapor attenuation with depth upon the estimated risk. The estimated indoor air concentration based upon the measured benzene concentration at 3 ft and 6 ft is $6.0 \times 10^{-3} \mu\text{g}/\text{m}^3$ (0.0019 ppb_{vv}) and $5.2 \times 10^{-3} \mu\text{g}/\text{m}^3$ (0.0016 ppb_{vv}), respectively. The individual excess cancer risk associated with these concentrations, using the Cal-EPA cancer slope factor of 0.1 kg-day/mg , is 5.3×10^{-8} and 4.6×10^{-8} , respectively. The estimated indoor air concentration for the surface measurements together with their associated individual excess cancer risks are summarized in Table 2.

Table 2 also presents the results of estimating the excess cancer risk for the standard RBCA Tier 2 vapor inhalation pathway based upon average measured ground water concentrations. The calculations were done both using the ASTM default geotechnical parameters (soil moisture, total porosity, and fraction organic carbon) and using measured site specific geotechnical parameters. While using measured site specific geotechnical parameters in many cases will result in a greater estimated attenuation of the inhalation pathway, it will generally be less than an order of magnitude difference.

Table 2 Estimated Individual Excess Cancer Risks Based Upon Case Study 2 Data.

Calculation Method	Benzene Surface Vapor Flux ($\mu\text{g}/\text{m}^2\text{-sec}$)	Calculated Excess Cancer Risk
RBCA Model		
Using ground water data (13 mg/L) and ASTM default parameters	1.0×10^{-5}	1.6×10^{-3}
Using ground water data (13 mg/L) and site-specific geotechnical parameters	9.0×10^{-6}	1.4×10^{-3}
Field Data		
Using averaged benzene surface flux	4.6×10^{-4}	7.2×10^{-6}
Using averaged soil vapor concentrations and site-specific geotechnical soil parameters		
3 ft	3.4×10^{-10}	5.3×10^{-8}
6 ft	2.9×10^{-10}	4.6×10^{-8}
8-9 ft	4.7×10^{-8}	7.4×10^{-6}

The large difference in risk values illustrated in Table 2 is attributable to an exponential decrease in hydrocarbon concentrations in soil vapor above the capillary fringe. The RBCA models do not predict these concentration decreases, which are clearly evident in the soil vapor profile data. Various mechanisms, particularly hydrocarbon biodegradation, may be responsible for the concentration decreases.

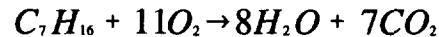
Simplified Biodegradation Stoichiometry

The sharp decrease in petroleum hydrocarbon concentrations with distance from the water table could be due to a number of factors including the presence of low permeability clay and soil heterogeneity, or biological degradation of petroleum hydrocarbons as they migrate to the surface. Because aerobic bacteria require oxygen (O_2) for the metabolism of petroleum hydrocarbons and produce carbon dioxide (CO_2) during the metabolism of petroleum hydrocarbons, a simple indicator of biological activity is decreased concentrations of O_2 and elevated concentrations of CO_2 in soil gas. The normal ambient concentration of O_2 and CO_2 in the atmosphere is about 21.6% O_2 and 355 ppm_{v/v} (0.035%) CO_2 .

Taking a closer look at the relationship between the concentration profiles of petroleum hydrocarbons, carbon dioxide, and oxygen for SVS sampling location closest to the petroleum hydrocarbon source area (Figure 2), a mass balance approach may be used to demonstrate an order of magnitude estimate of biodegradation stoichiometry (Ostendorf, 1991). If we assume that the attenuation of petroleum hydrocarbons

between 6 ft and 8 ft below ground surface (bgs) is the result of biological activity, then the flux of petroleum hydrocarbons upward from the source area (flux expressed in units of $\text{mol}/\text{m}^2\text{-sec}$) must be balanced by the flux of oxygen downwards from the surface. Degradation of the petroleum hydrocarbons will further result in the production and subsequent upward flux of carbon dioxide.

Assuming the petroleum hydrocarbons can be approximated as heptane, a simplified biodegradation stoichiometry is given by:



The stoichiometric ratio of oxygen to petroleum hydrocarbons would therefore be 11:1, the stoichiometric ratio of carbon dioxide to petroleum hydrocarbons would be 7:1, and the stoichiometric ratio of oxygen to carbon dioxide would be 1.6:1. We can then make an order of magnitude estimate of the petroleum hydrocarbon, oxygen, and carbon dioxide flux using Fick's law. For petroleum hydrocarbon flux we have (assuming petroleum hydrocarbons as heptane with a molecular weight of 100 g/mol):

$$F = D_{\text{eff},i} \cdot \frac{\Delta C_i}{\Delta y_i} = 3.8 \times 10^{-11} \frac{\text{mol}}{\text{m}^2\text{-sec}} \cdot \frac{(340,000 - 2,800) \frac{\text{ppm}}{\text{m}}}{(8 \text{ ft} - 6 \text{ ft})^{1.75 \pm 0.25}}$$

$$= 2.1 \times 10^{-2} \frac{\mu\text{g}}{\text{m}^2\text{-sec}}$$

$$= 2.1 \times 10^{-4} \frac{\mu\text{-mol}}{\text{m}^2\text{-sec}}$$

Where the subscript "i" represents a particular compound, in this case petroleum hydrocarbons, $D_{\text{eff},i}$ is the effective diffusivity, C_i is the soil vapor

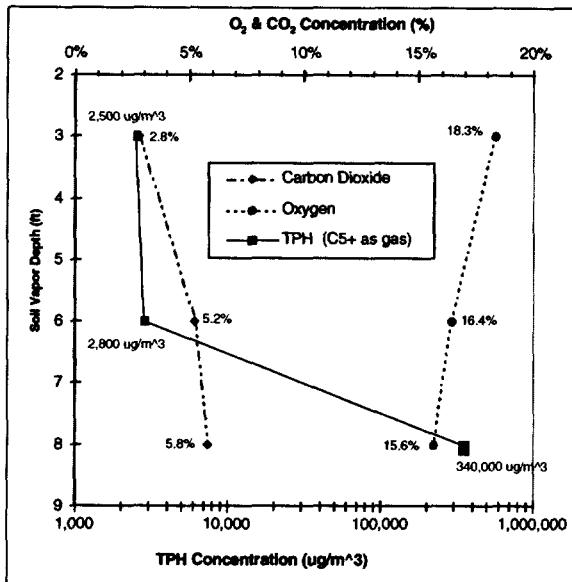


Figure 2: SVS results for sampling location nearest the source area

concentration, and y_i is the depth. Similarly for oxygen and carbon dioxide, the flux between 6-ft and 8-ft is calculated to be $1.6 \mu\text{g}/\text{m}^2\text{-sec}$ ($0.05 \mu\text{-mol}/\text{m}^2\text{-sec}$) and $1.3 \mu\text{g}/\text{m}^2\text{-sec}$ ($0.03 \mu\text{-mol}/\text{m}^2\text{-sec}$), respectively (positive flux assumed in the upward direction). The resulting stoichiometric ratio of oxygen to petroleum hydrocarbons is 223:1, the stoichiometric ratio of carbon dioxide to petroleum hydrocarbons is 138:1, and the stoichiometric ratio of oxygen to carbon dioxide is 1.6:1.

This order of magnitude estimate of the stoichiometric ratios demonstrates that there is sufficient oxygen diffusing downward and carbon dioxide diffusing upward to support the assumption of biological activity in the subsurface. In the case of

both oxygen and carbon dioxide, the ratio of oxygen or carbon dioxide to petroleum hydrocarbons is a factor of 20 higher than predicted by the simplified biodegradation stoichiometry. The elevated oxygen to petroleum hydrocarbons ratio indicates that there is sufficient oxygen diffusing downward to indicate that biodegradation of petroleum hydrocarbons is not oxygen limited.

The elevated carbon dioxide to petroleum hydrocarbon ratio indicates the presence of other degradable species not accounted for in the TPH analysis. While the exact agreement of the observed and predicted stoichiometric ratios of oxygen to carbon dioxide may be coincidental, it does clearly support the assumption of biological activity in the subsurface.

CASE STUDY 2: CHLORINATED HYDROCARBON CONTAMINATION SITE

The second case study was conducted at Lawrence Livermore National Laboratory (LLNL) Site 300, in two areas with potential VOC subsurface contamination. The emission isolation flux chamber methodology has been successfully applied at LLNL to the measurement of VOCs on two previous occasions (LLNL 1994 & 1995). Surface VOC flux measurements were used to support a screening of human health risks resulting from residual subsurface VOC contamination.

The case study addressed in this paper involved the collection of surface VOC flux measurements using the emission isolation flux chamber, and the collection of soil vapor depth profile using a combination drilling with soil vapor sampling capabilities. The surface flux measurements were collected to support a human

Table 3: Estimated exposure point concentrations of trichloroethylene based upon SVS data and collocated surface flux chamber data

Soil Vapor Survey Sampling Location	Soil Vapor Concentration at 10 ft ($\mu\text{g}/\text{m}^3$)	Estimated Flux ($\mu\text{g}/\text{m}^2\text{-sec}$)	Outdoor Conc. (ppb _{v/v})	Surface Flux Sampling Location	Measured Flux ($\mu\text{g}/\text{m}^2\text{-sec}$)	Outdoor Conc. (ppb _{v/v})
SVV-B854-24	796	1.66×10^{-4}	2.73×10^{-4}	3SF-B854-016	$<1.63 \times 10^{-3}$	$<2.69 \times 10^{-3}$
SVV-B854-29	2,700	5.61×10^{-4}	9.27×10^{-4}	3SF-B854-005	$<2.17 \times 10^{-3}$	$<3.58 \times 10^{-3}$
SVV-B854-32	11,870	2.47×10^{-3}	4.08×10^{-3}	3SF-B854-002	3.17×10^{-3}	5.23×10^{-3}
SVV-B854-33	10,075	2.10×10^{-3}	3.46×10^{-3}	3SF-B854-014	1.98×10^{-3}	3.27×10^{-3}
SVV-B854-34	590	1.23×10^{-4}	2.03×10^{-4}	3SF-B854-011	$<1.90 \times 10^{-3}$	$<3.14 \times 10^{-3}$
SVV-B854-35	1,575	3.28×10^{-4}	5.41×10^{-4}	3SF-B854-015	1.57×10^{-2}	2.59×10^{-2}
SVV-B830-031	57,837	1.20×10^{-2}	1.99×10^{-2}	3SF-B830-014	$<1.70 \times 10^{-3}$	$<2.81 \times 10^{-3}$
SVV-B830-032	2,303	4.79×10^{-4}	7.91×10^{-4}	3SF-B830-010	$<1.74 \times 10^{-3}$	$<2.87 \times 10^{-3}$
SVV-B830-033	30,912	6.43×10^{-3}	1.06×10^{-2}	3SF-B830-013	3.17×10^{-3}	5.23×10^{-3}
SVV-B830-034	2,274	4.73×10^{-4}	7.81×10^{-4}	3SF-B830-003	$<1.73 \times 10^{-3}$	$<2.86 \times 10^{-3}$
SVV-B830-035	1,055	2.19×10^{-4}	3.62×10^{-4}	3SF-B830-004	$<1.78 \times 10^{-3}$	$<2.94 \times 10^{-3}$

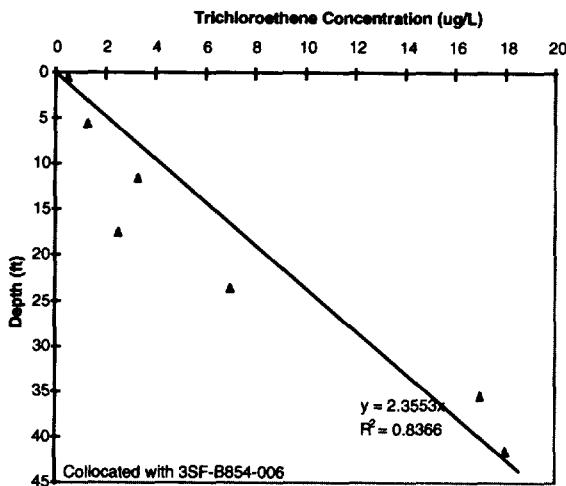


Figure 3: SVS depth profile for chlorinated hydrocarbon sample location SVV-B854-019

health risk screening. The SVS data was collected primarily as part of a characterization effort at the site. Where possible, however, surface flux measurement and SVS depth profiles were collocated to observe the possible correlation in the results.

Data was collected at two sites with potential VOC subsurface contamination. Investigation data and historic accounts collected for the two sites indicate that soils are contaminated with trichloroethylene (TCE). The source of the contamination is thought to be leaks from a TCE distribution system that was removed in the 1980s and from transfer and handling related spills. Boring logs indicate that TCE is present primarily in shallow soils but is found at over 30 ft bgs at the two sites. Residual TCE dense non-aqueous phase liquids (DNAPL) may also be present.

Potential sources of soil vapor flux from the first site, B854, were expected to result from shallow residual TCE DNAPLs. The depth to ground water at the B854 site is more than 100 ft. Potential sources of soil vapor flux from the second site, B830, were expected to result from both shallow residual TCE DNAPLs and a shallow perched ground water aquifer. The depth to the shallow perched ground water aquifer at the B830 site is approximately 25-ft.

Table 3 displays the results of the collocated soil vapor survey depth profiles and the surface flux measurements. To be able to compare the results, the outdoor air concentration was estimated based upon the results of each measurement technique. To estimate the soil vapor flux resulting from SVS data, the measured soil vapor depth profiles were plotted as shown in Figure 3. A linear approximation of the concentration gradient to the soil surface was used to estimate a soil vapor concentration at 10-ft bgs. The

estimated 10 ft soil vapor concentration was then used to estimate a surface vapor flux assuming ASTM default geotechnical parameters (soil moisture, total porosity, and effective diffusivity). For both the estimated flux based upon the SVS data and the measured flux based upon the emission isolation flux chamber data, the simple box model described earlier was applied to estimate outdoor air exposure point concentrations.

The correlation between the emission isolation flux chamber results and the SVS data is relatively good. The VOC surface flux observed at this site was very close to the detection limit of the emission isolation flux chamber methodology, whereas the soil vapor depth profiles provide a much lower detection limit. In three of the four emission isolation flux chamber samples where detectable VOC surface fluxes were observed, the VOC surface flux estimated based upon the SVS data was within a factor of two of the measured surface flux. The fourth emission isolation flux chamber sample where detectable VOC surface fluxes were observed in relatively high rates was likely due to the measurement of a former surface spill location.

Data at the B854 site is preliminary, and soil and ground water concentration data has not yet been published. For the B830 site, ground water data has been collected from the shallow perched ground water aquifer. Concentration of TCE in shallow perched ground water aquifer has ranged from 6 to 15 mg/L. The depth to the shallow perched ground water aquifer at the B830 site is approximately 25-ft.

Using the ASTM default geotechnical parameters (vadose zone soil moisture and porosity, capillary fringe thickness, porosity and moisture, and fraction organic carbon) these data result in an estimated soil vapor flux of $4.2 \times 10^{-2} \mu\text{g}/(\text{m}^2 \cdot \text{sec})$ and an estimated outdoor air concentration of $6.9 \times 10^{-2} \text{ ppb}_{\text{v/v}}$. This simple RBCA screening value is about an order of magnitude higher than the detection limit for the emission isolation flux chamber system used at this site and two orders of magnitude higher than the average soil vapor flux estimated based upon SVS data. Direct measurements of TCE vadose zone soil vapor concentration and soil vapor flux collected at this site underscore the conservative nature of the RBCA inhalation pathway models.

CONCLUSIONS

Emission isolation flux chamber measurements and soil vapor depth profiles are two methodologies for collecting direct measurements of parameters affecting the inhalation pathway resulting from subsurface contamination. The first case study examined the application of these techniques to a site

with petroleum hydrocarbon contamination. The second case study applied these techniques to a site with chlorinated hydrocarbon contamination.

In both cases lower surface vapor flux detection limits could be achieved by conservatively estimating flux based upon measured soil vapor depth profiles. Soil vapor data has additional value as a characterization tool. It can be also be argued that the soil vapor survey data is more representative of steady state soil vapor flux, and is less likely to be affected by subsurface soil heterogeneity and diurnal barometric effects

At the petroleum hydrocarbon site, soil vapor depth profiles exhibited an exponential concentration decrease in soil vapor with increasing height above the water table. Passive, long-term vapor samples confirmed that the profile data represents steady state conditions. The attenuating vapor concentrations in the vadose zone may be due to several factors. However, oxygen and carbon dioxide concentration profiles indicate that hydrocarbon biodegradation is probably the primary factor. Conservatively calculated estimates of indoor inhalation risk from field data were three to five orders of magnitude less than values predicted by the RBCA models.

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