Appendix B
Evaluation of Johnson and Ettinger Model for Estimating Subsurface Vapor Intrusion into Buildings

To: Peter Kelsall, Fort Ord Project Manager
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Date: May 6, 2004

Subject: Draft
Evaluation of Johnson and Ettinger Model for Estimating Subsurface Vapor Intrusion into Buildings
Carbon Tetrachloride Indoor Air Report
Former Fort Ord, California

Project Number: 4087040802-00112

This Memorandum provides an evaluation of the subsurface vapor intrusion model to predict indoor air concentrations of volatile organic compounds (VOCs) in residential structures in the vicinity of the carbon tetrachloride plume using soil gas data collected at the site. This analysis is provided to answer the following data quality objective (DQO) from the Indoor Air Sampling and Analysis Plan (SAP) (*Shaw, 2004*): Are concentrations of VOCs comparable to the concentrations predicted using the diffusion model? To answer this question, measured indoor air concentrations are compared with predicted indoor air concentrations which were modeled using the vapor intrusion model with measured soil gas data.

Indoor air concentrations of VOCs resulting from volatilization from the subsurface into indoor air can been estimated using the *Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings (Revised)* (*USEPA, 2000*), modified by the California Environmental Protection Agency, Department of Toxic Substances Control (Cal/EPA-DTSC) and contained in the soil gas screening model software available at the Cal/EPA-DTSC website:
http://www.dtsc.ca.gov/ScienceTechnology/JE_Models.html. This screening-level model incorporates both convective and diffusive mechanisms for estimating the transport of contaminant vapors emanating from soil gas into indoor spaces located directly above the source of contamination.

The measured soil gas data from the new 6-foot soil gas probe (SGP) probe and the 0.5-foot sub-slab probe were input into the model, along with site-specific parameters, to obtain estimated indoor air concentrations. All Cal/EPA-DTSC default values were used in the model, except for the following site-specific inputs:

- Depth below grade to bottom of enclosed-space floor: 15 centimeters (cm), which is the default value for slab-on grade. All of the residential structures in the area of the carbon tetrachloride plume are slab-on grade.

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- Soil gas sampling depth below grade: 183 cm for the 6-foot SGP probe and 15 cm for the 0.5-foot sub-slab probe.

- Vadose zone soil type: Sand. The soils in the area are predominantly sandy.

The predicted indoor air concentrations from the Johnson and Ettinger model from both the 6-foot SGP probe and 0.5-foot sub-slab probe are summarized in Table 1 along with the measured indoor air concentrations from the indoor air sampling within the building. The model was run for carbon tetrachloride, benzene, chloroform, and tetrachloroethene, which are the only four chemicals that were detected in both soil gas and indoor air samples collected at the site. The Johnson and Ettinger model worksheets are also attached for reference purposes.

As shown in Table 1, the modeled indoor air concentrations are between two and three orders of magnitude lower than the measured indoor air concentrations for all chemicals. Also, the 0.5-foot sub-slab modeling predicted higher indoor air concentrations than the 6-foot SGP modeling. The relative percent differences (RPDs) between the measured and modeled concentrations ranged from 174 to 199 percent (%). The correlation between the modeled indoor air concentrations using the 6-foot SGP data and the 0.5 foot sub-slab data was also low, with RPDs ranging from 16 to 170%.

As discussed in the Indoor Air Sampling Report (prepared by Shaw), the measured indoor air concentrations at the site are within the concentration range of background samples collected during the Fort Ord ambient air monitoring and are comparable with concentrations measured in the outdoor air sample collected at the site. The measured indoor air concentrations also significantly exceed the modeled indoor air concentrations predicted using the subsurface vapor intrusion model. These results indicate that the concentrations of VOCs in indoor air are consistent with expected concentrations from non-point sources in the area and suggest that the subsurface vapors from the carbon tetrachloride plume are not contributing significantly to VOCs in indoor air of the building.

Please call Edward Ticken at (707) 793-3882 if you have any questions.

Enclosures:
Table 1 – Summary of Modeled and Measured Indoor Air Concentrations
Attachment – Example Johnson and Ettinger Model Spreadsheets

References

Shaw Environmental, Inc. (Shaw), 2004. *Draft Final Sampling and Analysis Plan, Indoor Air Sampling, Operable Unit Carbon Tetrachloride Plume, Former Fort Ord, California*. Revision 0. March.

U.S. Environmental Protection Agency (EPA), 2000, *User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings (Revised)*. December. Cal/EPA-DTSC Modified. (http://www.dtsc.ca.gov/ScienceTechnology/JE_Models.html)

Table 1. Summary of Modeled and Measured Indoor Air VOC Concentrations
Carbon Tetrachloride Indoor Air Report
Former Fort Ord, California

Chemical	Sampling Date	Exterior Probe Soil Gas Concentration - 6 foot deep (ppbv)	Modeled Indoor Air Concentration from 6-foot Probe ($\mu g/m^3$) (a)	Modeled Indoor Air Concentration from 6-foot Probe (ppbv)	Measured Indoor Air Concentration (ppbv)	RPD Between 6-foot Probe Modeled and Measured Indoor Air Concentration
Carbon tetrachloride	3/9/2004	1.6E+00	6.5E-03	1.0E-03	9.9E-02	196%
Carbon tetrachloride	3/15/2004	1.5E+00	6.1E-03	9.6E-04	9.2E-02	196%
Benzene	3/9/2004	1.1E+00	2.5E-03	7.7E-04	2.2E-01	199%
Benzene	3/15/2004	2.0E+00	4.5E-03	1.4E-03	2.4E-01	198%
Chloroform	3/9/2004	5.6E-01	2.2E-03	4.4E-04	2.4E-02	193%
Chloroform	3/15/2004	5.3E-01	2.1E-03	4.2E-04	2.3E-02	193%
Tetrachloroethene	3/9/2004	7.6E-02	3.2E-04	4.6E-05	1.3E-02	199%
Tetrachloroethene	3/15/2004	8.9E-02	3.7E-04	5.4E-05	2.9E-02	199%

Chemical	Sampling Date	Sub-slab Probe Soil Gas Concentration - 0.5 foot deep (ppbv)	Modeled Indoor Air Concentration from 0.5-foot Sub-slab Probe ($\mu g/m^3$) (a)	Modeled Indoor Air Concentration from 0.5-foot Sub-slab Probe (ppbv)	Measured Indoor Air Concentration (ppbv)	RPD Between 0.5-foot Sub-slab Probe Modeled and Measured Indoor Air Concentration
Carbon tetrachloride	3/9/2004	2.8E+00	4.3E-02	6.8E-03	9.9E-02	174%
Carbon tetrachloride	3/15/2004	2.6E+00	4.0E-02	6.3E-03	9.2E-02	174%
Benzene	3/9/2004	3.9E+00	3.1E-02	9.5E-03	2.2E-01	184%
Benzene	3/15/2004	3.1E+00	2.4E-02	7.5E-03	2.4E-01	188%
Chloroform	3/9/2004	2.4E-01	2.9E-03	5.8E-04	2.4E-02	190%
Chloroform	3/15/2004	2.0E-01	2.4E-03	4.9E-04	2.3E-02	192%
Tetrachloroethene	3/9/2004	1.8E-01	7.5E-04	1.1E-04	1.3E-02	197%
Tetrachloroethene	3/15/2004	1.8E-01	7.5E-04	1.1E-04	2.9E-02	199%

Chemical	Sampling Date	Modeled Indoor Air Concentration from 6-foot probe (ppbv)	Modeled Indoor Air Concentration from 0.5-foot Sub-slab probe (ppbv)	RPD Between 6-foot Probe and 0.5-foot Sub slab Probe Modeled Indoor Air Concentrations
Carbon tetrachloride	3/9/2004	1.0E-03	6.8E-03	148%
Carbon tetrachloride	3/15/2004	9.6E-04	6.3E-03	147%
Benzene	3/9/2004	7.7E-04	9.5E-03	170%
Benzene	3/15/2004	1.4E-03	7.5E-03	137%
Chloroform	3/9/2004	4.4E-04	5.8E-04	28%
Chloroform	3/15/2004	4.2E-04	4.9E-04	16%
Tetrachloroethene	3/9/2004	4.6E-05	1.1E-04	81%
Tetrachloroethene	3/15/2004	5.4E-05	1.1E-04	68%

VOC Volatile organic compound.
RPD Relative percent difference.
µg/m3 Micrograms per cubic meter.
ppbv Parts per billion by volume.
(a) Modeled using the Johnson and Ettinger model, as described in text.

ATTACHMENT

EXAMPLE JOHNSON AND ETTINGER MODEL SPREADSHEETS

DATA ENTRY SHEET

SG-SCREEN
Version 2.0; 04/03

Reset to Defaults

DTSC / HERD
Version 2.0-mod3; 11/1/03
Default for Fine Soil

Soil Gas Concentration Data

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C_g ($\mu g/m^3$)	OR	ENTER Soil gas conc., C_g (ppmv)	Chemical
56235			1.50E-03	Carbon tetrachloride

MORE ↓

ENTER Depth below grade to bottom of enclosed space floor, L_F (15 or 200 cm)	ENTER Soil gas sampling depth below grade, L_s (cm)	ENTER Average soil temperature, T_S (°C)	ENTER Vadose zone SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined vadose zone soil vapor permeability, k_v (cm^2)
15	183	20	S		

MORE ↓

ENTER Vandose zone SCS soil type (Lookup Soil Parameters)	ENTER Vadose zone soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Vadose zone soil total porosity, n^V (unitless)	ENTER Vadose zone soil water-filled porosity, θ_w^V (cm^3/cm^3)	ENTER Average vapor flow rate into bldg. (Leave blank to calculate) Q_{soil} (L/m)
S	1.59	0.399	0.148	5

MORE ↓

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)
70	30	30	350

END

INTERMEDIATE CALCULATIONS SHEET

Source-building separation, L_T (cm)	Vadose zone soil air-filled porosity, θ_a^V (cm^3/cm^3)	Vadose zone effective total fluid saturation, S_{te} (cm^3/cm^3)	Vadose zone soil intrinsic permeability, k_i (cm^2)	Vadose zone soil relative air permeability, k_{rg} (cm^2)	Vadose zone soil effective vapor permeability, k_v (cm^2)	Floor-wall seam perimeter, X_{crack} (cm)	Soil gas conc. ($\mu g/m^3$)	Bldg. ventilation rate, $Q_{building}$ (cm^3/s)
168	0.251	0.275	1.01E-07	0.680	6.87E-08	4,000	9.59E+00	3.39E+04

Area of enclosed space below grade, A_B (cm^2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Z_{crack} (cm)	Enthalpy of vaporization at ave. soil temperature, $\Delta H_{v,TS}$ (cal/mol)	Henry's law constant at ave. soil temperature, H_{TS} (atm-m^3/mol)	Henry's law constant at ave. soil temperature, H'_{TS} (unitless)	Vapor viscosity at ave. soil temperature, μ_{TS} (g/cm-s)	Vadose zone effective diffusion coefficient, D^{eff}_V (cm^2/s)	Diffusion path length, L_d (cm)
1.00E+06	5.00E-03	15	7,757	2.43E-02	1.01E+00	1.78E-04	4.91E-03	168

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	Crack radius, r_{crack} (cm)	Average vapor flow rate into bldg., Q_{soil} (cm^3/s)	Crack effective diffusion coefficient, D^{crack} (cm^2/s)	Area of crack, A_{crack} (cm^2)	Exponent of equivalent foundation Peclet number, $\exp(Pe^f)$ (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)
15	9.59E+00	1.25	8.33E+01	4.91E-03	5.00E+03	5.52E+14	6.38E-04	6.12E-03

Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
4.2E-05	4.0E-02

END

DATA ENTRY SHEET

SG-SCREEN
Version 2.0; 04/03

Reset to Defaults

DTSC / HERD
Version 2.0-mod3; 11/1/03
Default for Fine Soil

Soil Gas Concentration Data

ENTER Chemical CAS No. (numbers only, no dashes)	ENTER Soil gas conc., C_g ($\mu g/m^3$)	OR	ENTER Soil gas conc., C_g (ppmv)	Chemical
56235			2.60E-03	Carbon tetrachloride

MORE ↓

ENTER Depth below grade to bottom of enclosed space floor, L_F (15 or 200 cm)	ENTER Soil gas sampling depth below grade, L_s (cm)	ENTER Average soil temperature, T_S (°C)	ENTER Vadose zone SCS soil type (used to estimate soil vapor permeability)	OR	ENTER User-defined vadose zone soil vapor permeability, k_v (cm^2)
15	15	20	S		

MORE ↓

ENTER Vandose zone SCS soil type	ENTER Vadose zone soil dry bulk density, ρ_b^A (g/cm^3)	ENTER Vadose zone soil total porosity, n^V (unitless)	ENTER Vadose zone soil water-filled porosity, θ_w^V (cm^3/cm^3)	ENTER Average vapor flow rate into bldg. (Leave blank to calculate) Q_{soil} (L/m)
S	1.59	0.399	0.148	5

Lookup Soil Parameters

MORE ↓

ENTER Averaging time for carcinogens, AT_C (yrs)	ENTER Averaging time for noncarcinogens, AT_{NC} (yrs)	ENTER Exposure duration, ED (yrs)	ENTER Exposure frequency, EF (days/yr)
70	30	30	350

END

INTERMEDIATE CALCULATIONS SHEET

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1	0.251	0.275	1.01E-07	0.680	6.87E-08	4,000	1.66E+01	3.39E+04

Area of enclosed space below grade, A_B (cm^2)	Crack-to-total area ratio, η (unitless)	Crack depth below grade, Z_{crack} (cm)	Enthalpy of vaporization at ave. soil temperature, $\Delta H_{v,TS}$ (cal/mol)	Henry's law constant at ave. soil temperature, H_{TS} (atm-m^3/mol)	Henry's law constant at ave. soil temperature, H'_{TS} (unitless)	Vapor viscosity at ave. soil temperature, μ_{TS} (g/cm-s)	Vadose zone effective diffusion coefficient, D^{eff}_V (cm^2/s)	Diffusion path length, L_d (cm)
1.00E+06	5.00E-03	15	7,757	2.43E-02	1.01E+00	1.78E-04	4.91E-03	1

Convection path length, L_p (cm)	Source vapor conc., C_{source} ($\mu g/m^3$)	Crack radius, r_{crack} (cm)	Average vapor flow rate into bldg., Q_{soil} (cm^3/s)	Crack effective diffusion coefficient, D^{crack} (cm^2/s)	Area of crack, A_{crack} (cm^2)	Exponent of equivalent foundation Peclet number, $\exp(Pe^f)$ (unitless)	Infinite source indoor attenuation coefficient, α (unitless)	Infinite source bldg. conc., $C_{building}$ ($\mu g/m^3$)
15	1.66E+01	1.25	8.33E+01	4.91E-03	5.00E+03	5.52E+14	2.42E-03	4.02E-02

Unit risk factor, URF ($\mu g/m^3)^{-1}$	Reference conc., RfC (mg/m^3)
4.2E-05	4.0E-02

END