ECF-200PO1-18-0082
Revision 0

ESTIMATION OF VAPOR/LIQUID PHASE EQUILIBRIUM VOLATILE ORGANIC COMPOUND CONCENTRATIONS AT THE AIR/WATER TABLE INTERFACE BENEATH NONRADIOACTIVE DANGEROUS WASTE LANDFILL

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company

P.O. Box 1600
Richland, Washington 99352

Approved for Public Release;
Further Dissemination Unlimited

ECF-200PO1-18-0082
Revision 0

ESTIMATION OF VAPOR/LIQUID PHASE EQUILIBRIUM VOLATILE ORGANIC COMPOUND CONCENTRATIONS AT THE AIR/WATER TABLE INTERFACE BENEATH NONRADIOACTIVE DANGEROUS WASTE LANDFILL

Date Published
April 2019

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company
P.O. Box 1600
Richland, Washington 99352

APPROVED
By Julia Raymer at 12:11 pm, Apr 09, 2019

Release Approval Date

Approved for Public Release;
Further Dissemination Unlimited

TRADEMARK DISCLAIMER

Reference herein to any specific commercial product, process, or service by tradename, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

This report has been reproduced from the best available copy.

Printed in the United States of America

ENVIRONMENTAL CALCULATION COVER PAGE

SECTION 1 - Completed by the Responsible Manager

Project:
Soil and Groundwater Remediation Project

RELEASE / ISSUE

Date: 02/26/2019

DATE: Apr 09, 2019 HANFORD RELEASE

Calculation Title and Description:
ESTIMATION OF VAPOR/LIQUID PHASE EQUILIBRIUM VOLATILE ORGANIC COMPOUND CONCENTRATIONS AT THE AIR/WATER TABLE INTERFACE BENEATH NONRADIOACTIVE DANGEROUS WASTE LANDFILL

Qualifications Summary

Preparer(s):

Name: Travis Hammond

Degree, Major, Institution, Year: MS Geological Sciences, Central Washington University, 2009
BS Medical Technology, Univ. South Alabama, 1994

Professional Licenses: Washington Licensed Professional Geologist

Brief Narrative of Experience: Travis Hammond has worked as a hydrogeologist for nine years with six of those years being on Hanford projects. Travis has extensive experience in groundwater chemistry and groundwater flow and contaminant transport. He is also versed in statistical and geostatistical methods. Mister Hammond has been involved with groundwater remediation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA), including preparation and implementation of CERCLA and RCRA decision documents and groundwater monitoring plans.

Checker(s):

Name: J. G. Douglas

Degree, Major, Institution, Year: MS Analytical Chemistry, Indiana University, 1984

Professional Licenses: NA

Brief Narrative of Experience: Thirty-four years experience in analytical chemistry including vapor analysis, extensive background in physical chemistry, nine years experience with Hanford Site groundwater monitoring program.

Senior Reviewer(s):

Name: Mary Hartman

Degree, Major, Institution, Year: M.S. Hydrogeology, University of Idaho, 1985

Professional Licenses: State of Washington geologist; hydrogeologist

Brief Narrative of Experience: 30 years working hydrogeologist at the Hanford Site

SECTION 2 - Completed by Preparer

Calculation Number: ECF-200PO1-18-0082 **Revision Number:** 0

Revision History

Revision No.	Description	Date	Affected Pages
0	Initial Release		All

ENVIRONMENTAL CALCULATION COVER PAGE (Continued)

SECTION 3 - Completed by the Responsible Manager

Document Control:

Is the document intended to be controlled within the Document Management Control System (DMCS)? (•) Yes ( ) No

Does document contain scientific and technical information intended for public use? (•) Yes ( ) No

Does document contain controlled-use information? ( ) Yes (•) No

SECTION 4 - Document Review and Approval

Preparer(s):			
Travis Hammond	Project Scientist		2/26/19
Print First and Last Name	*Position*	*Signature*	*Date*
Checker(s):			
J. G. Douglas	Chemist		2/26/2019
Print First and Last Name	*Position*	*Signature*	*Date*
Senior Reviewer(s):			
Mary Hartman	Sr. Project Scientist		3/1/2019
Print First and Last Name	*Position*	*Signature*	*Date*
Responsible Manager(s):			
William Faught	Manager		3/27/19
Print First and Last Name	*Position*	*Signature*	*Date*

SECTION 5 - Applicable if Calculation is a Risk Assessment or Uses an Environmental Model

Prior to Initiating Modeling:

Required training for modelers completed:
Integration Lead:

N/A		
Print First and Last Name	*Signature*	*Date*

Safety Software Approved:
Integration Lead:

N/A		
Print First and Last Name	*Signature*	*Date*

Calculation Approved:
Risk/Modeling Integration Manager:

N/A		
Print First and Last Name	*Signature*	*Date*

Contents

1 Purpose **1**

2 Background **1**

3 Methodology **2**

4 Assumptions and Inputs **3**

4.1 Assumptions 3

4.1.1 Henry's Law 3

4.1.2 Ideal Gas Law 4

4.2 Inputs 4

4.2.1 Henry's Law 4

4.2.2 Ideal Gas Law 4

5 Software Applications **9**

5.1 Approved Software 9

5.1.1 Description 9

5.1.2 Software Installation and Checkout 9

5.1.3 Statement of Valid Software Application 9

6 Calculation **9**

6.1 Henry's Law 9

6.2 Ideal Gas Law 10

7 Results/Conclusions **11**

8 References **15**

Appendix

Appendix A. NRDWL Equilibrium Calculations ..... A-i

Figures

Figure 1. NRDWL Groundwater and Soil Gas Monitoring Locations 12

Tables

Table 1. Constants Used in Henry's Law and Ideal Gas Law Equations 4

Table 2. Measured Parameters for and Estimated Parameters from the Henry's Law and Ideal Gas Law Equations 5

Table 3. Comparison of Estimated Vapor/Liquid Equilibrium Concentrations with Measured Soil Gas Concentrations from 1997 13

This page intentionally left blank.

Terms

bgs	below ground surface
DNAPL	dense non-aqueous phase liquid
ECF	environmental calculation file
HEIS	Hanford Environmental Information System
HISI	Hanford Information Systems Inventory
NRDWL	Non-radiological Dangerous Waste Landfill
PCE	tetrachloroethene
ppmv	parts-per-million by volume
SWL	Solid Waste Landfill
TCE	trichloroethene
TCFM	trichloromonofluoromethane
VLEC	vapor/liquid phase equilibrium concentration
VOC	volatile organic compound

This page intentionally left blank.

1 Purpose

The purpose of this environmental calculation file (ECF) is to document the process for the calculation of vapor/liquid phase equilibrium concentration (VLEC) estimates at the air/groundwater interface beneath the non-radiological dangerous waste landfill (NRDWL) at the Hanford Site. These estimates are needed to determine what soil vapor concentrations would be if soil-gas transport of volatile organic compounds (VOCs) were the primary source of VOC concentrations observed in groundwater at NRDWL.

2 Background

An important component of the site conceptual model for NRDWL is how soil vapor VOC concentrations relate to observed low-level groundwater VOC concentrations measured in the site's groundwater monitoring wells. Past soil gas surveys have identified the presence of vapor phase dense non-aqueous phase liquids (DNAPL) in the vadose zone beneath NRDWL (BHI-01115, *Evaluation of the Soil-Gas Survey at the Nonradioactive Dangerous Waste Landfill*, and BHI-01063, *Conceptual Model for the Solid Waste Landfill*) that are also present in groundwater. Specifically chloroform, trichloroethene (TCE), tetrachloroethene (PCE), and trichloromonofluoromethane (TCFM) have been measured at low-level concentrations in groundwater. Chloroform, PCE, TCE, and TCFM are DNAPLs that readily partition into liquid and vapor phases at equilibrium. Density driven transport of vapors from organic liquids can migrate considerable distances through the aerated porespace and cause extensive groundwater contamination (Mendoza and Frind, 1990, "Advective-dispersive Transport of Dense Organic Vapors in the Unsaturated Zone 1. Model Development;" Jang and Aral, 2007, "Density-driven Transport of Volatile Organic Compounds and its Impact on Contaminated Groundwater Plume Evolution"). To explain how soil vapors relate to groundwater concentrations, estimating the VLEC of VOCs detected in groundwater is key. This ECF details the estimation of the VLEC at the groundwater/air interface beneath NRDWL. Henry's law (Henry, 1803) states that the amount of dissolved gas is proportional to its partial pressure in the gas phase. The proportionality factor is called the Henry's law constant.

The ideal gas law and Henry's law can be used to estimate concentrations of dissolved VOCs in groundwater at equilibrium with soil vapor concentrations (see Section 6 for the ideal gas law and Henry's law equations). In order to use Henry's law to calculate the vapor/liquid phase equilibrium VOC concentrations, the partial pressures of the vapor phases of each VOC in the air/vapor mixture above the solution (groundwater) must be estimated. The partial pressure is calculated by multiplying the Henry's law constant by the vapor phase VOC concentration. Since no current soil vapor concentration data are available for NRDWL, it is necessary to estimate vapor phase concentrations using the ideal gas law. The mole fraction of each VOC in solution must also be calculated for use in the ideal gas law. VOC partial pressure is the essential unknown variable in the Henry's law calculation because of a lack of current soil vapor VOC concentration data at NRDWL.

The method described in this ECF was tested by comparing estimated VLECs from groundwater VOC concentrations collected in 1997 to actual deep soil gas measurements collected in 1997 at NRDWL (BHI-01115). This comparison demonstrated estimated soil vapor concentrations at the groundwater/air interface that where on average three orders of magnitude less than the soil vapor concentrations measured in 1997. However, the VLEC model assumes steady-state conditions and does not account for numerous dynamic vadose zone factors that can affect vapor concentrations (see Section 4). The results of this comparison are discussed in Section 7.

This calculation is part of the process to evaluate NRDWL as a possible source of chloroform, PCE, TCE, and TCFM groundwater contamination for the first determination as required by 40 CFR 265.93(d)(5), "Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and

Disposal Facilities," "Preparation, Evaluation, and Response." According to inventory tables in DOE/RL-90-17, *Nonradioactive Dangerous Waste Landfills/Solid Waste Landfill Closure/Postclosure Plan*, approximately 134 kg of chloroform, 620 kg of TCE, 342 kg of PCE, and 6 kg of Freon® (a major component of which is TCFM) were disposed in NRDWL.

A detailed discussion of the NRDWL facility description, operations history, regulatory basis, geology, hydrogeology, conceptual site model and groundwater monitoring network is provided in DOE/RL-2017-19, *Groundwater Quality Assessment Plan for the Nonradioactive Dangerous Waste Landfill, Hanford Site.* The adjacent Solid Waste Landfill (SWL) is also a known source of soil vapor and could also be a contributor to groundwater VOC concentrations (BHI-01063). From 1985 to 1987, approximately 380,000 liters of catch tank liquid from the 1100 Area heavy equipment garage and bus shop was disposed of in SWL (PNNL-13014, *Groundwater Monitoring Plan for the Solid Waste Landfill*). Catch tank liquid chemical analysis showed that the liquid contained TCE and PCE (DOE/RL-90-38, *Hanford Site Solid Waste Landfill Permit Application*). TCFM is a refrigerant and a major component of Freon and therefore is a likely component of the disposed catch tank liquid.

3 Methodology

This section provides the steps and associated calculation approach for estimating the VLEC of chloroform, PCE, TCE, and TCFM at the groundwater/air interface beneath NRDWL using Henry's law.

1. Compile groundwater VOC concentration data.

a. Groundwater data for all NRDWL wells (699-25-34B, 699-25-34D, 699-25-34F, 699-26-33A, 699-26-34A, 699-26-34B, 699-26-35A and 699-26-38) were downloaded from the Hanford Environmental Information System (HEIS) database for all groundwater sample analyses performed between April 2017 and April 2018. Dataset constituents include those listed in DOE/RL-2017-19.

b. The data were then screened well-by-well for consecutive occurrences of valid detections for further evaluation, which included comparing upgradient and downgradient concentrations and investigating site inventory. These evaluations yielded four possible VOC groundwater contaminants from NRDWL: chloroform in four wells, PCE in six wells, TCE in three wells and TCFM in two wells. Wells 699-25-33A, 699-26-34B and 699-26-38 did not have VOC detections. Details of the data validation procedure can be found in ECF-200PO1-18-0081, *Data Validation Procedure for RCRA Assessment First Determination Reports*.

c. Chloroform, PCE, and TCE data from 1997 were downloaded from HEIS for wells 699-25-33A, 699-25-34C, 699-25-34D, 699-26-33 and 699-26-34B. These values were used in the VLEC estimations that were compared to measured soil vapor chloroform, PCE, and TCE data from 1997. TCFM data were not downloaded from HEIS because that constituent was not measured in the 1997 survey. Only chloroform was detected in well 699-26-35C; therefore, chloroform was the constituent dataset retrieved from HEIS for that well.

2. Calculate estimated VLECs for chloroform, PCE, TCE, and TCFM using Henry's law. Further detail and specifics for methodology steps are discussed in Section 6.

a. Convert the aqueous groundwater VOC concentrations from µg/L to molarity (mol/L).

®Freon is a registered trademark of the Chemours Company FC, LLC (https://trademarks.justia.com/713/21/freon-71321938.html, https://www.chemours.com/Refrigerants/en_US/products/Freon/).

b. Compile published Henry's law constants (K_H) at 20°C for chloroform, PCE, TCE, and TCFM. The K_H for chloroform, PCE and TCE were obtained from *EPA On-line Tools for Site Assessment Calculation* (EPA, 2016) for a temperature of 20°C. The K_H for TCFM was obtained from *Compilation of Henry's law constants (version 4.0) for water as solvent* (Sander, 2015) at 20°C and required conversion from mol/m^3-Pa to atm-L/mol.

c. Using Henry's law, calculate the partial pressure of each VOC using the data compiled in Steps 1, 2a, and 2b. This assumes that the VOC vapor concentration is in equilibrium with the VOC aqueous concentration at the air/water table interface.

d. Estimate the vapor-phase concentrations of chloroform, PCE, TCE, and TCFM at the air/water table interface for each groundwater sample using the ideal gas law. Parameters for this calculation include the partial pressure of the VOC (Step c), formula weight, the ideal gas constant (0.0821 atm-L/mol-K), and 293 K (20 °C). The temperature of 20 °C was chosen because it represents a good average for the Hanford Site vadose zone at depths ~140 feet below ground surface for the air/water table interface beneath NRDWL (BNWL-1712, *A Study of Soil Water Potential and Temperature in Hanford Soils*). The methodology is described further in Section 6.

4 Assumptions and Inputs

This section provides the relevant assumptions and inputs necessary to perform the calculations, including a brief explanation of the basis for each and the methodology it supports.

4.1 Assumptions

These estimations of VOC concentrations using the methods described in this ECF are solely for the purpose of validating the conceptual model for soil vapor VOC dissolution into groundwater as a pathway of groundwater contamination at NRDWL. Due to the large inherent uncertainty in variable estimations in the natural deep vadose zone system at NRDWL, the estimated VLECs are intended only to be representative values of conditions at the air/water interface at the time of groundwater sampling and are not intended to be hindcasts of actual concentrations. Some of the factors that influence soil-gas profiles include geologic properties of the vadose zone, soil-moisture content, temperature, depth to ground water and ground-water flow rate, phase separation, soil-organic content, temperature and temperature gradients, water-table oscillations, lithology of the aquifer, barometric effects, and rainfall.

Another major uncertainty is that the calculations performed in this document assume steady-state equilibrium conditions and thus do not account for the dynamic conditions of the site vadose zone and water table. The calculations do not account for dispersion or advection dilution upon vapor dissolution into groundwater. Vapor sampling depths were also shallower (from 18.3 to 29.3 meters below ground surface [bgs]) than the depth to groundwater of about 42 meters bgs at NRDWL. Actual DNAPL vapor concentrations could be lower at the groundwater/air interface than at the soil vapor measuring depths. Consequently, interpretation of soil-gas data is complex and highly site specific.

4.1.1 Henry's Law

The primary assumption of Henry's law (Section 3, Step 2c) is that at low solute concentrations, the solvent (water) is in large excess and therefore solvent molecules are likely to be surrounded by other solvent molecules. Consequently, the behavior of the solvent is much like that of the pure liquid solvent. The solute, on the other hand, is in low concentration, so solute molecules are likely to be surrounded by solvent molecules. Thus, their environment is quite different from the pure solute environment, and consequently their behavior is greatly modified.

4.1.2 Ideal Gas Law

The ideal gas law used to estimate vapor-phase VOC concentrations (Section 3, Step 2d) assumes that 1) the gas consists of a large number of molecules which are in random motion and obey Newton's laws of motion; 2) the volume of the molecules is negligibly small compared to the volume occupied by the gas; and 3) no forces act on the molecules except during elastic collisions of negligible duration. A temperature of 293 K (20 °C) is used in the ideal gas law equation.

4.2 Inputs

4.2.1 Henry's Law

Inputs for the Henry's law equation for calculating the estimated vapor/liquid equilibrium concentrations (Section 3, Step 2c) for chloroform, PCE, TCE, and TCFM include VOC aqueous-phase molar concentrations for each VOC. Constants including K_H at 20°C are listed in Table 1.

4.2.2 Ideal Gas Law

Inputs for the ideal gas law for estimating vapor-phase VOC concentrations (Section 3, Step 2d) include the estimated VOC partial pressure from Henry's law, formula weight of the VOC, ideal gas constant, and temperature of 293 K. Constants including formula weight, ideal gas constant, and temperature values are listed in Table 1. Measured and estimated parameters including VOC groundwater concentrations, estimated partial pressures, estimated vapor-phase concentrations and VLEC are listed in Table 2.

Table 1. Constants Used in Henry's Law and Ideal Gas Law Equations

VOC	Formula Weight (g/mol)	K_H (atm-L/mol) at 20°C	Ideal Gas Constant (atm-L/mol-K)	Temperature (K)
Chloroform	119.37	2.95E-6[a]	0.0821	293 (20°C)
Tetrachloroethene	165.82	1.39E-5[a]		
Trichloroethene	131.38	8.06E-6[a]		
Trichloro-monoflouromethane	137.36	8.97E-6[b]		

Sources: Vapor pressure - chloroform, PCE and TCE are from *Engineering ToolBox*, (2006), "Vapor Pressure Common Liquids."

K_H - chloroform, PCE and TCE are from EPA (2016), *EPA On-line Tools for Site Assessment Calculation.*

TCFM – Sander (2015), *Compilation of Henry's Law Constants (version 4.0) for Water as Solvent.*

a. Converted from atm-m^3/mol

b. Converted value. See Section 6 for conversion.

PCE = tetrachloroethene

TCE = trichloroethene

TCFM = trichloromonofluoromethane

VOC = volatile organic compound

Table 2. Measured Parameters for and Estimated Parameters from the Henry's Law and Ideal Gas Law Equations

Well Name	Constituent	Sample Date	Solution Conc. (µg/L)	Solution Conc. (mol/L)	HL Const. K_H (atm-L/mol)	HL Partial Pres. (atm)	HL Vapor Conc. (mol/L)	HL Vapor Conc. (mg/L)	HL Vapor Conc. (ppmv)
699-25-34B	Chloroform	4/12/2017	0.27	2.26E-09	2.95E-06	6.67E-15	2.77E-16	3.31E-11	6.67E-09
699-25-34B	Chloroform	4/12/2017	0.28	2.35E-09	2.95E-06	6.92E-15	2.88E-16	3.43E-11	6.92E-09
699-25-34B	Chloroform	7/17/2017	0.23	1.93E-09	2.95E-06	5.68E-15	2.36E-16	2.82E-11	5.68E-09
699-25-34B	Chloroform	10/19/2017	0.34	2.85E-09	2.95E-06	8.40E-15	3.49E-16	4.17E-11	8.40E-09
699-25-34B	Chloroform	10/19/2017	0.35	2.93E-09	2.95E-06	8.65E-15	3.60E-16	4.29E-11	8.65E-09
699-25-34B	Chloroform	1/8/2018	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34B	Chloroform	1/8/2018	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34B	Chloroform	4/24/2018	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34B	Chloroform	4/24/2018	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34B	Tetrachloroethene	4/12/2017	0.59	3.56E-09	1.39E-05	4.95E-14	2.06E-15	3.41E-10	4.95E-08
699-25-34B	Tetrachloroethene	4/12/2017	0.63	3.80E-09	1.39E-05	5.28E-14	2.20E-15	3.64E-10	5.28E-08
699-25-34B	Tetrachloroethene	7/17/2017	0.39	2.35E-09	1.39E-05	3.27E-14	1.36E-15	2.25E-10	3.27E-08
699-25-34B	Tetrachloroethene	10/19/2017	0.61	3.68E-09	1.39E-05	5.11E-14	2.13E-15	3.52E-10	5.11E-08
699-25-34B	Tetrachloroethene	10/19/2017	0.63	3.80E-09	1.39E-05	5.28E-14	2.20E-15	3.64E-10	5.28E-08
699-25-34B	Tetrachloroethene	1/8/2018	0.57	3.44E-09	1.39E-05	4.78E-14	1.99E-15	3.29E-10	4.78E-08
699-25-34B	Tetrachloroethene	1/8/2018	0.55	3.32E-09	1.39E-05	4.61E-14	1.92E-15	3.18E-10	4.61E-08
699-25-34B	Tetrachloroethene	4/24/2018	0.45	2.71E-09	1.39E-05	3.77E-14	1.57E-15	2.60E-10	3.77E-08
699-25-34B	Tetrachloroethene	4/24/2018	0.48	2.89E-09	1.39E-05	4.02E-14	1.67E-15	2.77E-10	4.02E-08
699-25-34B	Trichloroethene	4/12/2017	0.36	2.74E-09	8.06E-06	2.21E-14	9.18E-16	1.21E-10	2.21E-08
699-25-34B	Trichloroethene	4/12/2017	0.39	2.97E-09	8.06E-06	2.39E-14	9.95E-16	1.31E-10	2.39E-08
699-25-34B	Trichloroethene	7/17/2017	0.25	1.90E-09	8.06E-06	1.53E-14	6.38E-16	8.38E-11	1.53E-08
699-25-34B	Trichloroethene	10/19/2017	0.39	2.97E-09	8.06E-06	2.39E-14	9.95E-16	1.31E-10	2.39E-08
699-25-34B	Trichloroethene	10/19/2017	0.34	2.59E-09	8.06E-06	2.09E-14	8.67E-16	1.14E-10	2.09E-08
699-25-34B	Trichloroethene	1/8/2018	0.35	2.66E-09	8.06E-06	2.15E-14	8.93E-16	1.17E-10	2.15E-08
699-25-34B	Trichloroethene	1/8/2018	0.34	2.59E-09	8.06E-06	2.09E-14	8.67E-16	1.14E-10	2.09E-08
699-25-34B	Trichloroethene	4/24/2018	0.3	2.28E-09	8.06E-06	1.84E-14	7.65E-16	1.01E-10	1.84E-08
699-25-34B	Trichloroethene	4/24/2018	0.33	2.51E-09	8.06E-06	2.02E-14	8.42E-16	1.11E-10	2.02E-08
699-25-34B	Trichloromonofluoromethane	4/12/2017	0.37	2.69E-09	8.97E-06	2.42E-14	1.00E-15	1.38E-10	2.42E-08
699-25-34B	Trichloromonofluoromethane	4/12/2017	0.41	2.98E-09	8.97E-06	2.68E-14	1.11E-15	1.53E-10	2.68E-08
699-25-34B	Trichloromonofluoromethane	7/17/2017	0.46	3.35E-09	8.97E-06	3.00E-14	1.25E-15	1.72E-10	3.00E-08
699-25-34B	Trichloromonofluoromethane	10/19/2017	0.31	2.26E-09	8.97E-06	2.02E-14	8.42E-16	1.16E-10	2.02E-08

Table 2. Measured Parameters for and Estimated Parameters from the Henry's Law and Ideal Gas Law Equations

Well Name	Constituent	Sample Date	Solution Conc. (µg/L)	Solution Conc. (mol/L)	HL Const. K_H (atm-L/mol)	HL Partial Pres. (atm)	HL Vapor Conc. (mol/L)	HL Vapor Conc. (mg/L)	HL Vapor Conc. (ppmv)
699-25-34B	Trichloromonofluoromethane	10/19/2017	0.33	2.40E-09	8.97E-06	2.15E-14	8.96E-16	1.23E-10	2.15E-08
699-25-34B	Trichloromonofluoromethane	1/8/2018	0.34	2.48E-09	8.97E-06	2.22E-14	9.23E-16	1.27E-10	2.22E-08
699-25-34B	Trichloromonofluoromethane	1/8/2018	0.34	2.48E-09	8.97E-06	2.22E-14	9.23E-16	1.27E-10	2.22E-08
699-25-34B	Trichloromonofluoromethane	4/24/2018	0.3	2.18E-09	8.97E-06	1.96E-14	8.14E-16	1.12E-10	1.96E-08
699-25-34B	Trichloromonofluoromethane	4/24/2018	0.3	2.18E-09	8.97E-06	1.96E-14	8.14E-16	1.12E-10	1.96E-08
699-26-35A	Trichloromonofluoromethane	4/11/2017	0.37	2.69E-09	8.97E-06	2.42E-14	1.00E-15	1.38E-10	2.42E-08
699-26-35A	Trichloromonofluoromethane	7/18/2017	0.3	2.18E-09	8.97E-06	1.96E-14	8.14E-16	1.12E-10	1.96E-08
699-26-35A	Trichloromonofluoromethane	10/16/2017	0.3	2.18E-09	8.97E-06	1.96E-14	8.14E-16	1.12E-10	1.96E-08
699-26-35A	Trichloromonofluoromethane	1/9/2018	0.41	2.98E-09	8.97E-06	2.68E-14	1.11E-15	1.53E-10	2.68E-08
699-26-35A	Trichloromonofluoromethane	4/23/2018	0.42	3.06E-09	8.97E-06	2.74E-14	1.14E-15	1.57E-10	2.74E-08
699-25-34D	Tetrachloroethene	4/12/2017	0.54	3.26E-09	1.39E-05	4.53E-14	1.88E-15	3.12E-10	4.53E-08
699-25-34D	Tetrachloroethene	10/19/2017	0.59	3.56E-09	1.39E-05	4.95E-14	2.06E-15	3.41E-10	4.95E-08
699-25-34D	Tetrachloroethene	1/11/2018	0.42	2.53E-09	1.39E-05	3.52E-14	1.46E-15	2.43E-10	3.52E-08
699-25-34D	Tetrachloroethene	4/24/2018	0.57	3.44E-09	1.39E-05	4.78E-14	1.99E-15	3.29E-10	4.78E-08
699-25-34D	Trichloroethene	4/12/2017	0.36	2.74E-09	8.06E-06	2.21E-14	9.18E-16	1.21E-10	2.21E-08
699-25-34D	Trichloroethene	10/19/2017	0.32	2.44E-09	8.06E-06	1.96E-14	8.16E-16	1.07E-10	1.96E-08
699-25-34D	Trichloroethene	1/11/2018	0.35	2.66E-09	8.06E-06	2.15E-14	8.93E-16	1.17E-10	2.15E-08
699-25-34D	Trichloroethene	4/24/2018	0.32	2.44E-09	8.06E-06	1.96E-14	8.16E-16	1.07E-10	1.96E-08
699-25-34F	Chloroform	4/11/2017	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34F	Chloroform	7/18/2017	0.37	3.10E-09	2.95E-06	9.14E-15	3.80E-16	4.54E-11	9.14E-09
699-25-34F	Chloroform	10/16/2017	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-25-34F	Chloroform	1/11/2018	0.41	3.43E-09	2.95E-06	1.01E-14	4.21E-16	5.03E-11	1.01E-08
699-25-34F	Chloroform	4/24/2018	0.39	3.27E-09	2.95E-06	9.64E-15	4.01E-16	4.78E-11	9.64E-09
699-25-34F	Tetrachloroethene	4/11/2017	0.48	2.89E-09	1.39E-05	4.02E-14	1.67E-15	2.77E-10	4.02E-08
699-25-34F	Tetrachloroethene	7/18/2017	0.61	3.68E-09	1.39E-05	5.11E-14	2.13E-15	3.52E-10	5.11E-08
699-25-34F	Tetrachloroethene	10/16/2017	0.54	3.26E-09	1.39E-05	4.53E-14	1.88E-15	3.12E-10	4.53E-08
699-25-34F	Tetrachloroethene	1/11/2018	0.54	3.26E-09	1.39E-05	4.53E-14	1.88E-15	3.12E-10	4.53E-08
699-25-34F	Tetrachloroethene	4/24/2018	0.81	4.88E-09	1.39E-05	6.79E-14	2.82E-15	4.68E-10	6.79E-08
699-25-34F	Trichloroethene	4/11/2017	0.32	2.44E-09	8.06E-06	1.96E-14	8.16E-16	1.07E-10	1.96E-08
699-25-34F	Trichloroethene	7/18/2017	0.34	2.59E-09	8.06E-06	2.09E-14	8.67E-16	1.14E-10	2.09E-08
699-25-34F	Trichloroethene	10/16/2017	0.3	2.28E-09	8.06E-06	1.84E-14	7.65E-16	1.01E-10	1.84E-08

Table 2. Measured Parameters for and Estimated Parameters from the Henry's Law and Ideal Gas Law Equations

Well Name	Constituent	Sample Date	Solution Conc. (µg/L)	Solution Conc. (mol/L)	HL Const. K_H (atm-L/mol)	HL Partial Pres. (atm)	HL Vapor Conc. (mol/L)	HL Vapor Conc. (mg/L)	HL Vapor Conc. (ppmv)
699-25-34F	Trichloroethene	1/11/2018	0.35	2.66E-09	8.06E-06	2.15E-14	8.93E-16	1.17E-10	2.15E-08
699-25-34F	Trichloroethene	4/24/2018	0.44	3.35E-09	8.06E-06	2.70E-14	1.12E-15	1.47E-10	2.70E-08
699-26-33A	Tetrachloroethene	4/11/2017	0.53	3.20E-09	1.39E-05	4.44E-14	1.85E-15	3.06E-10	4.44E-08
699-26-33A	Tetrachloroethene	7/18/2017	0.37	2.23E-09	1.39E-05	3.10E-14	1.29E-15	2.14E-10	3.10E-08
699-26-33A	Tetrachloroethene	10/16/2017	0.3	1.81E-09	1.39E-05	2.51E-14	1.05E-15	1.73E-10	2.51E-08
699-26-33A	Tetrachloroethene	1/11/2018	0.35	2.11E-09	1.39E-05	2.93E-14	1.22E-15	2.02E-10	2.93E-08
699-26-33A	Tetrachloroethene	4/23/2018	0.29	1.75E-09	1.39E-05	2.43E-14	1.01E-15	1.68E-10	2.43E-08
699-26-34A	Tetrachloroethene	4/12/2017	0.37	2.23E-09	1.39E-05	3.10E-14	1.29E-15	2.14E-10	3.10E-08
699-26-34A	Tetrachloroethene	7/17/2017	0.3	1.81E-09	1.39E-05	2.51E-14	1.05E-15	1.73E-10	2.51E-08
699-26-34A	Tetrachloroethene	10/18/2017	0.37	2.23E-09	1.39E-05	3.10E-14	1.29E-15	2.14E-10	3.10E-08
699-26-34A	Tetrachloroethene	1/8/2018	0.33	1.99E-09	1.39E-05	2.77E-14	1.15E-15	1.91E-10	2.77E-08
699-26-34A	Tetrachloroethene	4/23/2018	0.18	1.09E-09	1.39E-05	1.51E-14	6.27E-16	1.04E-10	1.51E-08
699-26-35A	Chloroform	4/11/2017	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-26-35A	Chloroform	7/18/2017	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-26-35A	Chloroform	10/16/2017	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09
699-26-35A	Chloroform	1/9/2018	0.12	1.01E-09	2.95E-06	2.97E-15	1.23E-16	1.47E-11	2.97E-09
699-26-35A	Chloroform	4/23/2018	0.14	1.17E-09	2.95E-06	3.46E-15	1.44E-16	1.72E-11	3.46E-09
699-26-35A	Tetrachloroethene	4/11/2017	0.38	2.29E-09	1.39E-05	3.19E-14	1.32E-15	2.20E-10	3.19E-08
699-26-35A	Tetrachloroethene	7/18/2017	0.3	1.81E-09	1.39E-05	2.51E-14	1.05E-15	1.73E-10	2.51E-08
699-26-35A	Tetrachloroethene	10/16/2017	0.32	1.93E-09	1.39E-05	2.68E-14	1.12E-15	1.85E-10	2.68E-08
699-26-35A	Tetrachloroethene	1/9/2018	0.33	1.99E-09	1.39E-05	2.77E-14	1.15E-15	1.91E-10	2.77E-08
699-26-35A	Tetrachloroethene	4/23/2018	0.37	2.23E-09	1.39E-05	3.10E-14	1.29E-15	2.14E-10	3.10E-08
699-26-35C	Chloroform	4/11/2017	0.11	9.22E-10	2.95E-06	2.72E-15	1.13E-16	1.35E-11	2.72E-09
699-26-35C	Chloroform	7/18/2017	0.1	8.38E-10	2.95E-06	2.47E-15	1.03E-16	1.23E-11	2.47E-09
699-26-35C	Chloroform	10/18/2017	0.12	1.01E-09	2.95E-06	2.97E-15	1.23E-16	1.47E-11	2.97E-09
699-26-35C	Chloroform	1/8/2018	0.1	8.38E-10	2.95E-06	2.47E-15	1.03E-16	1.23E-11	2.47E-09
699-26-35C	Chloroform	4/23/2018	0.16	1.34E-09	2.95E-06	3.95E-15	1.64E-16	1.96E-11	3.95E-09

Conc. = concentration
HL = Henry's law (value is estimated from Henry's law)
ppmv = parts-per-million by volume
Pres. = pressure

This page intentionally left blank.

5 Software Applications

Microsoft® Excel® software is approved and appropriate applications for this calculation. Excel was used to perform data sorting and basic arithmetic calculations and R was used for statistical calculations.

5.1 Approved Software

Microsoft Excel is approved under PRC-PRO-IRM-309, *Software Control Management* and is registered on the Hanford Information System Inventory (HISI) and identified as approved for use.

5.1.1 Description

- Microsoft® Excel®
- Software Version: 2016
- HISI Identification Number: 1915 (as part of the Site-standard Microsoft Office suite)
- Workstation type and property number: Dell Laptop WF37103

5.1.2 Software Installation and Checkout

Excel is site-standard software and does not require a software installation and checkout form.

5.1.3 Statement of Valid Software Application

The calculations performed within this ECF were within the limits of the approved software.

6 Calculation

All calculations (including unit conversions) involved in the steps leading up to and including the VLEC estimation, were performed in Excel. Equations for the ideal gas law and Henry's law are listed below.

6.1 Henry's Law

The basic concept behind the partitioning of volatile contaminants from the aqueous phase to the gaseous phase (and vice versa) is Henry's law, which states, for a given temperature, there is a linear relationship between the equilibrium vapor pressure of a solute above its aqueous solution and its concentration in the solution. The proportionality constant between the two is the Henry's law constant. The equation for Henry's law is as follows:

$$K_H = \frac{P}{C} \qquad \text{Equation 1}$$

Where

K_H = Henry's law constant (atm-L/mol); K_H is temperature dependent and the temperature at which K_H is determined should be stated with the value of K_H.

P = partial pressure of the ga-phase VOC at equilibrium (atm)

C = solution-phase concentration at equilibrium (mol/L)

® Microsoft and Excel are registered trademarks of the Microsoft Corporation in the United States and other countries.

K_H for chloroform, PCE, and TCE were obtained from EPA (2016) in atm-L/mol, but the TCFM constant of 1.1 x 10^{-4} mol/m^3-Pa (Sander, 2015) required the following conversion:

$$K_H = \left(9.86923E^{-6}\,\frac{atm}{Pa} \div 1.1E^{-4}\,\frac{mol}{m^3\,Pa} \times \frac{1E^3 L}{m^3}\right) = 8.97E^{-6}\ atm - L/_{mol} \qquad \text{Equation 2}$$

P is estimated using K_H and the groundwater-phase concentration C (mol/L) by rearranging $K_H = \frac{P}{C}$ Equation 1 as:

$$P = C \times K_H \qquad \text{Equation 3}$$

6.2 Ideal Gas Law

The estimated VOC vapor concentrations were calculated using the ideal gas law. The ideal gas law equation is as follows:

$$PV = nRT \qquad \text{Equation 4}$$

Where

P = pressure (atm)

V = volume (L)

n = number of moles of VOC

R = ideal gas constant (0.08206 atm-L/mol-K)

T = temperature (K)

$PV = nRT$ Equation 4 can be rearranged as follows to give the vapor-phase concentration of the VOC in moles/liter:

$$n/V = P/(RT) \qquad \text{Equation 5}$$

The vapor-phase concentration in moles/liter may then be converted to mass (g/L) by multiplying n/V by the formula weight (g/mol) of the VOC.

The vapor-phase concentration of the VOC in liters solute per liter of gas sample (V/V concentration) is determined as follows:

$$P_1V_1 = P_2V_2 \qquad \text{Equation 6}$$

$P_1V_1 = P_2V_2$ Equation *6* rearranges to:

$$V_2/_{V_1} = P_1/_{P_2} \qquad \text{Equation 7}$$

Where V_1 = one liter, V_2 = volume (L) of VOC at one atmosphere, P_1 = partial pressure of VOC (atm) as determined by Henry's law ($P = C \times K_H$ Equation 3), and P_2 = one atmosphere. The result may be multiplied by 10^6 to generate the V/V concentration in parts-per-million by volume (ppmv) for comparison with actual vapor-phase concentration measurements. The numerical result in ppmv is easily determined by multiplying the Henry's law partial pressure (Equation 3) by 10^6.

7 Results/Conclusions

The ideal gas law and Henry's law calculations and results derived using the April 2017 to April 2018 groundwater VOC concentrations are shown in Table 2. These results indicate what the soil vapor concentrations would be if steady-state equilibrium soil-gas transport of VOCs were the primary source of VOC contamination observed in groundwater at NRDWL. To determine the extent to which soil-gas transport is the actual source of VOC contamination in groundwater, additional deep soil-gas sampling is needed for comparison of estimated VLECs to actual soil-gas concentrations at the air/groundwater interface.

Results of the comparison of estimated VLECs for 1997 chloroform, PCE and TCE groundwater to soil vapor concentrations collected in 1997 are listed in Table 3. Because the calculations indicate that transport phenomena outweigh steady-state equilibria, estimated VLECs were considerably lower than the 1997 soil vapor measurements (Table 3). Figure 1 shows the locations of the soil vapor measuring sites and monitoring wells. The results indicate that dynamic vadose zone and groundwater factors such as decreased vapor concentrations with depth, vapor dilution from dispersion in the vadose zone, and advective and diffusional VOC dilution in groundwater result in groundwater VOC concentrations much less than would be measured under steady-state equilibrium conditions.

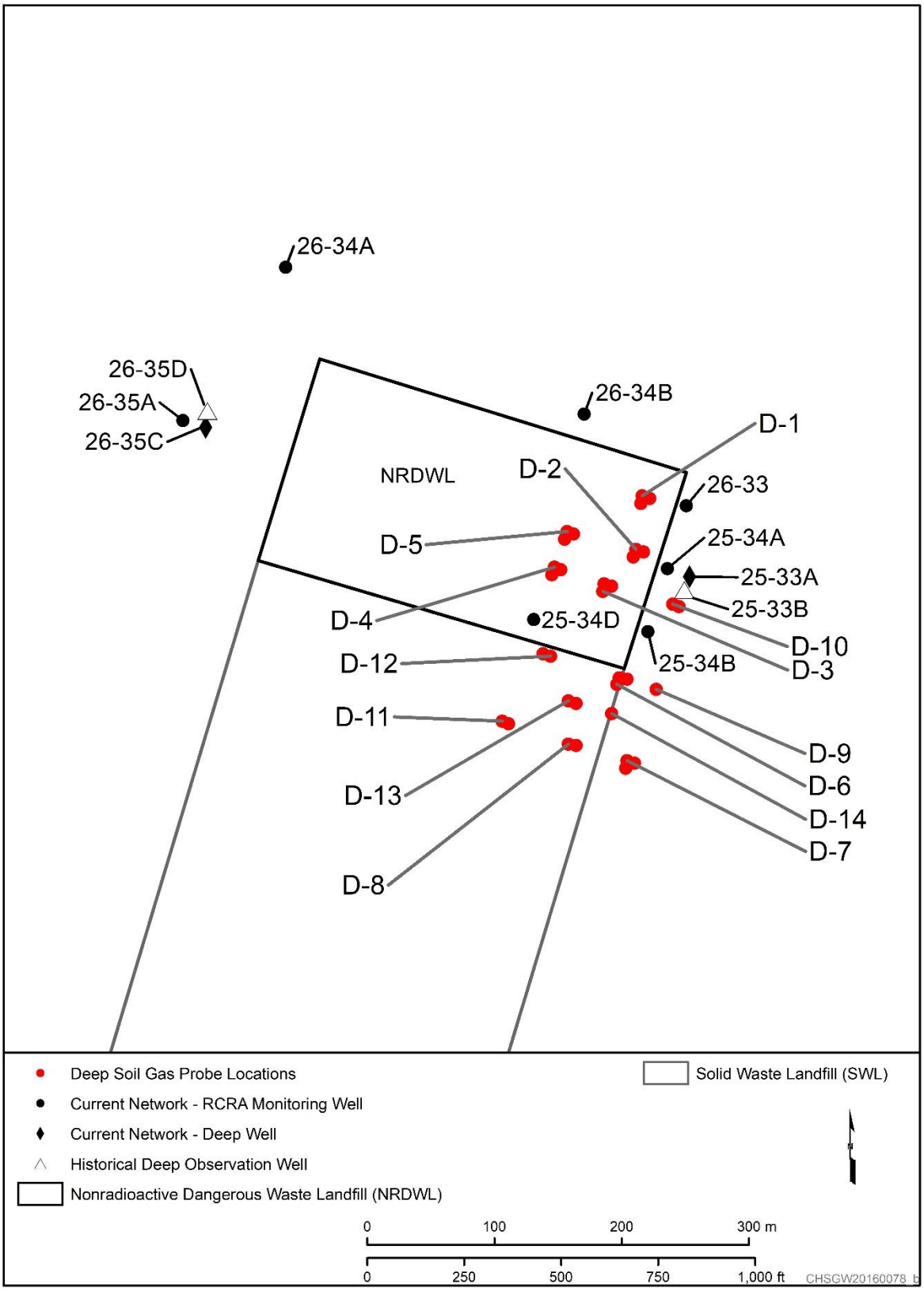

Figure 1. NRDWL Groundwater and Soil Gas Monitoring Locations

Table 3. Comparison of Estimated Vapor/Liquid Equilibrium Concentrations with Measured Soil Gas Concentrations from 1997

Well Name	Constituent	Sample Date	Solution Conc. (µg/L)	Solution Conc. (mol/L)	HL Const. K_H (atm-L/mol)	HL Partial Pres. (atm)	HL Vapor Conc. (mol/L)	HL Vapor Conc. (mg/L)	HL Vapor Conc. (ppmv)	Measured Vapor Conc. (ppmv)	Vapor Sample Date	Probe Number	Probe Depth (m)
699-25-33A	Chloroform	2/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/2/1997	D-10	25.1
699-25-33A	Chloroform	8/13/1997	0.028	2.35E-10	2.95E-06	6.92E-16	2.88E-17	3.43E-12	6.92E-10	< 0.1	9/4/1997	D-2	29.3
699-25-34B	Chloroform	2/13/1997	0.4	3.35E-09	2.95E-06	9.89E-15	4.11E-16	4.91E-11	9.89E-09	< 0.1	9/2/1997	D-10	25.1
699-25-34B	Chloroform	8/13/1997	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09	< 0.1	9/2/1997	D-10	25.1
699-25-34C	Chloroform	2/18/1997	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09	< 0.1	9/2/1997	D-7	26.4
699-25-34C	Chloroform	5/15/1997	0.28	2.35E-09	2.95E-06	6.92E-15	2.88E-16	3.43E-11	6.92E-09	< 0.1	9/2/1997	D-7	26.4
699-25-34C	Chloroform	8/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/2/1997	D-11	18.3
699-25-34C	Chloroform	8/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/2/1997	D-11	18.3
699-25-34C	Chloroform	12/8/1997	0.28	2.35E-09	2.95E-06	6.92E-15	2.88E-16	3.43E-11	6.92E-09	< 0.1	9/2/1997	D-11	18.3
699-25-34D	Chloroform	2/13/1997	0.3	2.51E-09	2.95E-06	7.41E-15	3.08E-16	3.68E-11	7.41E-09	0.17	9/2/1997	D-12	18.6
699-25-34D	Chloroform	8/18/1997	0.1	8.38E-10	2.95E-06	2.47E-15	1.03E-16	1.23E-11	2.47E-09	0.17	9/2/1997	D-12	18.6
699-26-33	Chloroform	2/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/4/1997	D-1	25.9
699-26-33	Chloroform	8/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/4/1997	D-1	25.9
699-26-34B	Chloroform	2/12/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/4/1997	D-1	25.9
699-26-34B	Chloroform	8/18/1997	0.2	1.68E-09	2.95E-06	4.94E-15	2.05E-16	2.45E-11	4.94E-09	< 0.1	9/4/1997	D-1	25.9
699-25-33A	Tetrachloroethene	2/18/1997	0.2	1.21E-09	1.39E-05	1.68E-14	6.97E-16	1.16E-10	1.68E-08	< 0.1	9/2/1997	D-10	25.1
699-25-33A	Tetrachloroethene	8/13/1997	0.031	1.87E-10	1.39E-05	2.60E-15	1.08E-16	1.79E-11	2.60E-09	0.2	9/4/1997	D-2	29.3
699-25-34C	Tetrachloroethene	2/18/1997	1.4	8.44E-09	1.39E-05	1.17E-13	4.88E-15	8.09E-10	1.17E-07	< 0.1	9/2/1997	D-7	26.4
699-25-34C	Tetrachloroethene	5/15/1997	1.1	6.63E-09	1.39E-05	9.22E-14	3.83E-15	6.36E-10	9.22E-08	< 0.1	9/2/1997	D-7	26.4
699-25-34C	Tetrachloroethene	8/18/1997	1	6.03E-09	1.39E-05	8.38E-14	3.48E-15	5.78E-10	8.38E-08	0.11	9/2/1997	D-12	18.6
699-25-34C	Tetrachloroethene	8/18/1997	1	6.03E-09	1.39E-05	8.38E-14	3.48E-15	5.78E-10	8.38E-08	0.095	9/2/1997	D-11	18.3
699-25-34C	Tetrachloroethene	12/8/1997	1.3	7.84E-09	1.39E-05	1.09E-13	4.53E-15	7.51E-10	1.09E-07	0.12	9/2/1997	D-11	26.2
699-25-34D	Tetrachloroethene	2/13/1997	1	6.03E-09	1.39E-05	8.38E-14	3.48E-15	5.78E-10	8.38E-08	0.11	9/2/1997	D-12	18.6
699-25-34D	Tetrachloroethene	8/18/1997	2	1.21E-08	1.39E-05	1.68E-13	6.97E-15	1.16E-09	1.68E-07	0.11	9/2/1997	D-12	18.6
699-26-33	Tetrachloroethene	2/18/1997	0.7	4.22E-09	1.39E-05	5.87E-14	2.44E-15	4.04E-10	5.87E-08	0.27	9/4/1997	D-1	25.9
699-26-33	Tetrachloroethene	8/18/1997	0.7	4.22E-09	1.39E-05	5.87E-14	2.44E-15	4.04E-10	5.87E-08	0.27	9/4/1997	D-1	25.9
699-26-34B	Tetrachloroethene	2/12/1997	0.6	3.62E-09	1.39E-05	5.03E-14	2.09E-15	3.47E-10	5.03E-08	0.27	9/4/1997	D-1	25.9
699-26-34B	Tetrachloroethene	8/18/1997	0.5	3.02E-09	1.39E-05	4.19E-14	1.74E-15	2.89E-10	4.19E-08	0.27	9/4/1997	D-1	25.9
699-25-33A	Trichloroethene	2/18/1997	0.2	1.52E-09	8.06E-06	1.23E-14	5.10E-16	6.70E-11	1.23E-08	< 0.1	9/2/1997	D-10	25.1
699-25-33A	Trichloroethene	8/13/1997	0.028	2.13E-10	8.06E-06	1.72E-15	7.14E-17	9.38E-12	1.72E-09	0.25	9/2/1997	D-11	18.3
699-25-34C	Trichloroethene	2/18/1997	0.9	6.85E-09	8.06E-06	5.52E-14	2.30E-15	3.02E-10	5.52E-08	0.25	9/2/1997	D-11	18.3
699-25-34C	Trichloroethene	5/15/1997	0.76	5.78E-09	8.06E-06	4.66E-14	1.94E-15	2.55E-10	4.66E-08	0.25	9/2/1997	D-11	18.3
699-25-34C	Trichloroethene	8/18/1997	0.6	4.57E-09	8.06E-06	3.68E-14	1.53E-15	2.01E-10	3.68E-08	0.25	9/2/1997	D-11	18.3

Table 3. Comparison of Estimated Vapor/Liquid Equilibrium Concentrations with Measured Soil Gas Concentrations from 1997

Well Name	Constituent	Sample Date	Solution Conc. (µg/L)	Solution Conc. (mol/L)	HL Const. K_H (atm-L/mol)	HL Partial Pres. (atm)	HL Vapor Conc. (mol/L)	HL Vapor Conc. (mg/L)	HL Vapor Conc. (ppmv)	Measured Vapor Conc. (ppmv)	Vapor Sample Date	Probe Number	Probe Depth (m)
699-25-34C	Trichloroethene	8/18/1997	0.7	5.33E-09	8.06E-06	4.29E-14	1.79E-15	2.35E-10	4.29E-08	0.25	9/2/1997	D-11	18.3
699-25-34C	Trichloroethene	12/8/1997	0.88	6.70E-09	8.06E-06	5.40E-14	2.24E-15	2.95E-10	5.40E-08	0.25	9/2/1997	D-11	18.3
699-25-34D	Trichloroethene	2/13/1997	0.6	4.57E-09	8.06E-06	3.68E-14	1.53E-15	2.01E-10	3.68E-08	0.072	9/2/1997	D-12	18.6
699-25-34D	Trichloroethene	8/18/1997	0.9	6.85E-09	8.06E-06	5.52E-14	2.30E-15	3.02E-10	5.52E-08	0.072	9/2/1997	D-12	18.6
699-26-33	Trichloroethene	2/18/1997	0.4	3.04E-09	8.06E-06	2.45E-14	1.02E-15	1.34E-10	2.45E-08	< 0.1	9/4/1997	D-1	25.9
699-26-33	Trichloroethene	8/18/1997	0.4	3.04E-09	8.06E-06	2.45E-14	1.02E-15	1.34E-10	2.45E-08	< 0.1	9/4/1997	D-1	25.9
699-26-34B	Trichloroethene	2/12/1997	0.3	2.28E-09	8.06E-06	1.84E-14	7.65E-16	1.01E-10	1.84E-08	< 0.1	9/4/1997	D-1	25.9
699-26-34B	Trichloroethene	8/18/1997	0.3	2.28E-09	8.06E-06	1.84E-14	7.65E-16	1.01E-10	1.84E-08	< 0.1	9/4/1997	D-1	25.9

Conc. = concentration
HL = Henry's law (value is estimated from Henry's law)
ppmv = parts-per-million by volume
Pres. = pressure

8 References

40 CFR 265, "Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities," *Code of Federal Regulations*. Available at: https://www.govregs.com/regulations/title40_chapterI_part265_subpartF_section265.93.

265.93, "Preparation, Evaluation, and Response."

BHI-01063, 1997, *Conceptual Model for the Solid Waste Landfill*, Rev. 0, Bechtel Hanford, Inc., Richland, Washington. Available at: http://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=00099104.

BHI-01115, 1997, *Evaluation of the Soil-Gas Survey at the Nonradioactive Dangerous Waste Landfill*, Rev. 0, Bechtel Hanford, Inc., Richland, Washington. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=D197301462.

BNWL-1712, 1973, *A Study of Soil Water Potential and Temperature in Hanford Soils*, Battelle Pacific Northwest Laboratories, Richland, WA. Available at: https://pdw.hanford.gov/arpir/pdf.cfm?accession=D196018255

DOE/RL-90-17, 2010, *Nonradioactive Dangerous Waste Landfills/Solid Waste Landfill Closure/Postclosure Plan*, Rev. 2, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=1101200569.

DOE/RL-90-38, 1993, *Hanford Site Solid Waste Landfill Permit Application*, Rev. 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=1107141083.

DOE/RL-2017-19, 2017, *Groundwater Quality Assessment Plan for the Nonradioactive Dangerous Waste Landfill, Hanford Site*, Rev. 0, Department of Energy, Richland Operations Office, Richland, Washington. Available at: https://pdw.hanford.gov/arpir/index.cfm/viewDoc?accession=0072142H.

ECF-200PO1-18-0081, 2018, *Data Validation Procedure for RCRA Assessment First Determination Reports*, Rev. 0, Department of Energy, Richland Operations Office, Richland, Washington. Pending.

Engineering ToolBox, 2006, "Vapor Pressure common Liquids." [online] Available at: https://www.engineeringtoolbox.com/vapor-pressure-d_312.html. Accessed 12/6/2018.

EPA, 2016, *EPA On-line Tools for Site Assessment Calculation*. [online] Available at: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/esthenry.html. Accessed 12/6/2018.

Henry, W., 1803, "Experiments on the Quantity of Gases Absorbed by Water, at Different Temperatures, and Under Different Pressures." *Philosophical Transactions of the Royal Society*, London, 93: 29–274. Available at: https://royalsocietypublishing.org/doi/10.1098/rstl.1803.0004.

Jang, W. and M.M. Aral, 2007, "Density-driven Transport of Volatile Organic Compounds and its Impact on Contaminated Groundwater Plume Evolution," *Transport in Porous Media*, 67:353-374. Available at: https://link.springer.com/article/10.1007%2Fs11242-006-9029-8.

Mendoza, C.A. and E.O. Frind, 1990, "Advective-dispersive Transport of Dense Organic Vapors in the Unsaturated Zone 1. Model Development," *Water Resources Research*, 26:379-387. Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/WR026i003p00379.

PNNL-13014, 2000, *Groundwater Monitoring Plan for the Solid Waste Landfill*, Pacific Northwest National Laboratory, Richland, Washington. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-13014.pdf.

PRC-PRO-IRM-309, 2018, *Controlled Software Management*, Rev. 5, CH2M Hill Plateau Remediation Company, Richland, WA.

Sander, R. 2015, Compilation of Henry's Law Constants (version 4.0) for Water as Solvent, *Atmospheric Chemistry and Physics*, 15:4399-4981. Available at: https://www.atmos-chem-phys.net/15/4399/2015/acp-15-4399-2015.pdf.

Appendix A

NRDWL Equilibrium Calculations

Calculations performed as described in Sections 3 and 6 of this ECF were carried out in the Microsoft Excel® spreadsheet provided on the removable media.

Microsoft Excel® Spreadsheet
NRDWL Equilibrium Calculations.xlsx

® Microsoft Excel is a registered trademark of Microsoft Corporation in the United States and other countries.

This page intentionally left blank.