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Treatability Test of a Stacked-Tray Air Stripper for VOCs in Water

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Abstract

A common strategy for hydraulic containment and mass removal at VOC contaminated sites is "pump and treat (P&T)". In P&T operations, contaminated ground water is pumped from wells, treated above ground, and discharged. Many P&T remediation systems at VOC sites rely on air stripping technology because VOCs are easily transferred to the vapor phase. In stacked-tray air strippers, contaminated water is aerated while it flows down through a series of trays. System operations at LLNL are strictly regulated by the California and federal Environmental Protection Agencies (Cal/EPA and EPA), the Bay Area Air Quality Management District (BAAQMD), the California Regional Water Quality Control Board (RWQCB) and the Department of Toxic Substances Control (DTSC). These agencies set discharge limits, require performance monitoring, and assess penalties for non-compliance. National laboratories are also subject to scrutiny by the public and other government agencies. This extensive oversight makes it necessary to accurately predict field treatment performance at new extraction locations to ensure compliance with all requirements prior to facility activation. This paper presents treatability test results for a stacked-tray air stripper conducted at LLNL and compares them to the vendor's modeling software results.

Introduction

Volatile organic compounds (VOCs) have been commonly used for dry cleaning and degreasing since the early 1900s. Leaks from storage tanks, distribution pipelines, and past disposal practices have led to chlorinated solvent ground water contamination. Ground water under Lawrence Livermore National Laboratory (LLNL) contains VOCs including, trichloroethylene (TCE) tetrachloroethylene (PCE), 1,1-dichloroethlyene (1,1-DCE), 1,2-dichloroethane (1,2-DCA), chloroform (CF), and carbon tetrachloride (CT). The highest total VOC concentration onsite is approximately 6 milligrams per liter (mg/L). The surface discharge limit is 5 micrograms per liter (µg/L) total VOCs.

The most common remedial strategy for VOC plumes is "pump and treat (P&T)," whereby contaminated ground water is extracted from wells, treated at the surface, and discharged. LLNL's Record of Decision (ROD) selected remedies include P&T using ex-situ air stripping of VOCs abated by vapor-phase granular activated carbon.

Air stripping is the process of bubbling air through water to remove volatile substances, including VOCs, from the water. The most common types of air stripping systems are packed tower aeration, diffused air strippers, and stacked-tray air strippers. In stacked-tray systems, contaminated water enters from the top and is aerated while it flows down through a series of trays. Air is forced up from the bottom creating a "froth" to allow contaminant mass transfer from liquid to vapor. Stacked-tray air strippers are widely used for contaminant mass removal and hydraulic tests at both of LLNL's Superfund sites.

Environmental cleanup operations at LLNL are regulated by the California and federal Environmental Protection Agencies (Cal/EPA and EPA), the Bay Area Air Quality Management District (BAAQMD), the California Regional Water Quality Control Board (RWQCB), and the Department of Toxic Substances Control (DTSC).

These agencies set discharge limits, require performance monitoring, and assess penalties for noncompliance. National laboratories are also subjected to scrutiny by the public and other government agencies. This oversight makes accurate prediction of field treatment performance prior to facility activation desirable to ensure compliance with all regulatory requirements and to ensure cost-effective air stripper selection.

This paper compares field treatability data from ShallowTray Model 2331 air stripper to the modeling results from the vendor's proprietary software. The treatability test results are used to determine the necessary air flow rate and to predict the effluent water concentration at new extraction locations.

Air Stripping Theory

Air stripper theory from Henry's Law to more general mass transfer between water and air is developed in the following section. The specific case of a stacked-tray air stripper treating VOCs is evaluated.

Stripping order is the rank from highest to lowest Henry's constant which represents the comparative ease of air stripping. For example, at equal concentrations and a constant air-to-water flow ratio, a greater fraction of 1,1-DCE will be removed than CT.

Henry's Law

For dilute solutions at equilibrium, the mole fraction of gas in water is proportional to the mole fraction of gas in air. The constant of proportionality is called the Henry's constant, expressed as the vapor pressure divided by the solubility in water. A comparison of the Henry's constant for contaminants of concern is presented in Table 1. Low values for Henry's constant indicate the chemical is difficult to air strip.

Mass Transfer via Two-Film Theory

The degree to which the gas-water system deviates from equilibrium provides the driving force for diffusion. For gas to diffuse from water to air, a concentration gradient in the direction of transfer must exist. The kinetics of gas transfer are modeled via the two-film theory. Transport requires movement: from the bulk solution, through the liquid film to the interface, from the interface through the gas film, and from the film into the bulk gas. The concentration gradient between the bulk solutions and the interface drives diffusion.

If dilute conditions exist, then Henry's Law applies and mole fraction in liquid is proportional to the mole fraction in air at equilibrium. For highly volatile compounds with large Henry's constants, the liquid-phase resistance controls the diffusion rate. With these simplifying assumptions, the mass transfer per unit time is equal to a constant times the air-to-water concentration gradient. The constant with units of inverse time is empirically determined and is dependent on the water quality and the specific equipment used.

For VOC transfer from liquid to air, analysis of the concentration gradient is difficult because the partial pressure of the VOC starts at zero in the atmosphere and increases as the bubble moves through the contaminated water. Therefore, mass transfer per unit time must be solved using a mass balance approach, or setting the total mass of gas loss from the water volume equal to the total mass transfer into the air volume.

Stacked-Tray Air Stripper

The ShallowTray Model 2331 is a cascading tray

TABLE 1: Henry's Constants for Select VOCs at 68°F

	TCE	PCE	1,1-DCE	1,2-DCA	CF	CT
H (atm)	544	1035	1841	51	171	1282
Hm (atm-m^3/mol)	9.8×10^{-3}	1.9×10^{-2}	3.3×10^{-2}	9.2×10^{-4}	3.1×10^{-3}	2.3×10^{-2}
H_u (dimensionless)	0.400	0.762	1.355	0.038	0.126	0.944
Stripping Order	4	3	1	6	5	2

Source: (Nyer, 1992)

TABLE 2: Potential Test Well Comparison

Well Identification	Concentration (µg/L) TCE	PCE	1,1-DCE	1,2-DCA	CF	CT	Freon 113	Total
W-352	1100	80	37	7.1	46	6.1	16	1292
W-361	2700	410	230	130	8.5	5.6	<10	3484
W-423	2.2	0.7	<0.5	<0.5	1.8	<0.5	130	135
W-610	25	7.7	11	<0.5	0.63	0.76	4.1	49
W-1109	2100	590	280	<10	<10	<10	48	3018

Note: "<0.5" means non-detect reported at a detection limit of 0.5 ug/L.

aerator with a spray nozzle inlet. Mass transfer takes place during spraying, during aeration within the tray, and in falling laminar sheets as water drops from one tray to the next. Mass transfer data on this type of combined system are not available in the literature, therefore design must be based on experience (AWWA, 1990). Modeling this air stripper including effects of relative concentration between contaminants, temperature effects, and other variables, requires the results of site-specific treatability tests.

Treatability Test

In 1995, we activated the first portable stacked-tray air stripper based groundwater treatment system, designated Portable Treatment Unit (PTU), at LLNL replacing stationary tank-style diffused air stripper designs. The PTU, shown in Figure 1, is a cargo transportainer-based ground water treatment system containing a particulate filter, a stacked-tray air stripper, vapor-phase carbon abatement, and optional sequestering agent injection and pH control system. The PTU's control system provides operational interlocks, is fail-safe allowing unattended operation, and features remote or local data display (Bahowick, 1996). During activation, treatability tests were conducted to assess the performance of the air stripper in removing VOCs and to compare the performance to the ShallowTray Modeler estimations.

The following sections summarize the selection of test wells and air-to-water ratios, field test procedure, results, and predictions.

Test Well VOC Concentrations

The highest concentration and mass rate wells from LLNL's Livermore Site were determined by examining the database. The final well selection candidates are presented in Table 2. Wells W-352 and W-361 were chosen as test wells to provide a range of VOCs, particularly the harder to strip compounds 1,2-DCA and CF.

Air-To-Water Ratio Selection

The PTU's BAAQMD permit contains a condition limiting the influent water flow rate based on the influent VOC concentration in water. This restriction limited the selection of air-to-water ratio combinations that could be performed. The maximum allowable flow rate for well W-361 is 20 gallons per minute (gpm), and 50 gpm for well W-352. The ShallowTray Model 2331 is normally operated at a constant airflow rate of 300 cubic

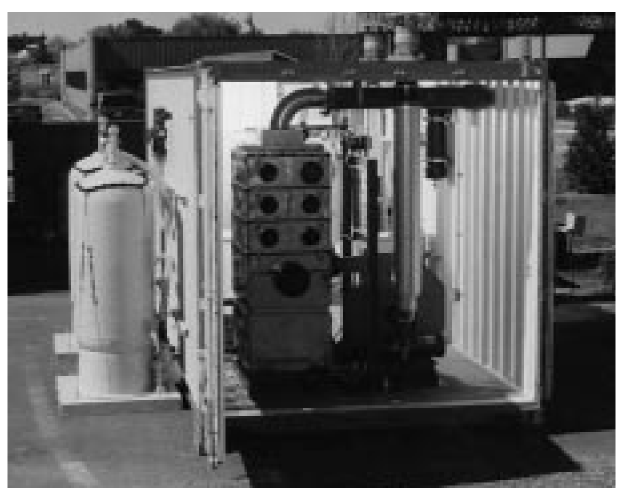

Figure 1. The stacked-tray air stripper used for treatability testing is shown here within a PTU.

TABLE 3: Empirical Stripping Constants

	TCE	PCE	1,1-DCE	1,2-DCA	CF	CT
Stripping Constant, K (gal/ft^3)	0.622	0.646	0.656	0.291	0.394	0.403
Stripping Order	3	2	1	6	5	4

feet per minute (cfm) throughout the 0.5 to 50 gpm hydraulic range, as recommended by the manufacturer. In order to vary the air-to-water ratio and stay within permit limitations, both the air and water flows were adjusted. Adjusting the damper changed the airflow rate. The water flow rate was adjusted by throttling the pump with a globe valve.

Field Test Procedure

Water from the test wells was pumped into a portable closed-top tank, and samples were collected. A portable pump was used to pump water from the tank into the PTU. The PTU's stacked-tray air stripper provided treatment prior to being collected in a 4,000 gallon closed-top tank to hold for additional treatment prior to discharge, if necessary. During this process, air and water flow rates were varied. Water flow was measured using a magnetic flow meter that infers flow from the movement of a conducting fluid through a magnetic field. Airflow was measured using a pitot tube and a hand-held anemometer.

Sampling was conducted in accordance with LLNL's Environmental Restoration Project Standard Operating Procedures (SOPs) (Dibley and Depue, 1997). Influent and effluent samples were collected for VOC analysis by EPA Method 601 at a commercial laboratory. Duplicates were sent to another laboratory for Quality Control. Additional sampling was conducted both to ensure adequate water treatment below discharge levels before release and to check compliance with BAAQMD and RWQCB permits. The test procedure described above was repeated for each test well at a series of air-to-water ratios to determine the air strippers' removal efficiency for each VOC.

Treatability Test Results

All analytical results were reviewed according with LLNL's Environmental Restoration Project SOPs to ensure consistent results of a known quality. Results with poor data quality were flagged as suspect and eliminated from further analysis. For each combination of airflow rate, water flow rate, and effluent concentration, the fraction remaining after stripping was calculated by dividing the effluent concentration by the average influent concentration. Whenever the effluent concentration was below the detection limit, the fraction remaining was calculated but not used further. The remaining fractional results were plotted on a log scale against the volumetric air-to-water ratio, or airflow in cfm divided by the water flow in gpm. An exponential curve was fitted to the data. When there is no airflow, the stripping factor is zero and the effluent concentration should theoretically equal the influent concentration. Therefore, the y-intercept should be one, so the curve fit was forced through it. The treatability test data and fitted curves are presented in Figure 2 for each VOC. Empirically derived stripping constants were obtained from the exponential equations of the curve fitted lines. The resulting stripping constants and stripping order are presented in Table 3.

Effluent Concentration Prediction Using Field Data

The stripping constants given in Table 3 can be used to predict treatment performance. The first-order decay model is used to describe the fraction remaining in the following equation:

$$c_e/c_i = e^{-Kq},$$

where:

c_e = effluent water conc.,
c_i = influent water conc.,
K = stripping constant, gal/ft^3,
q = volumetric air-to-water ratio, ft^3/gal.

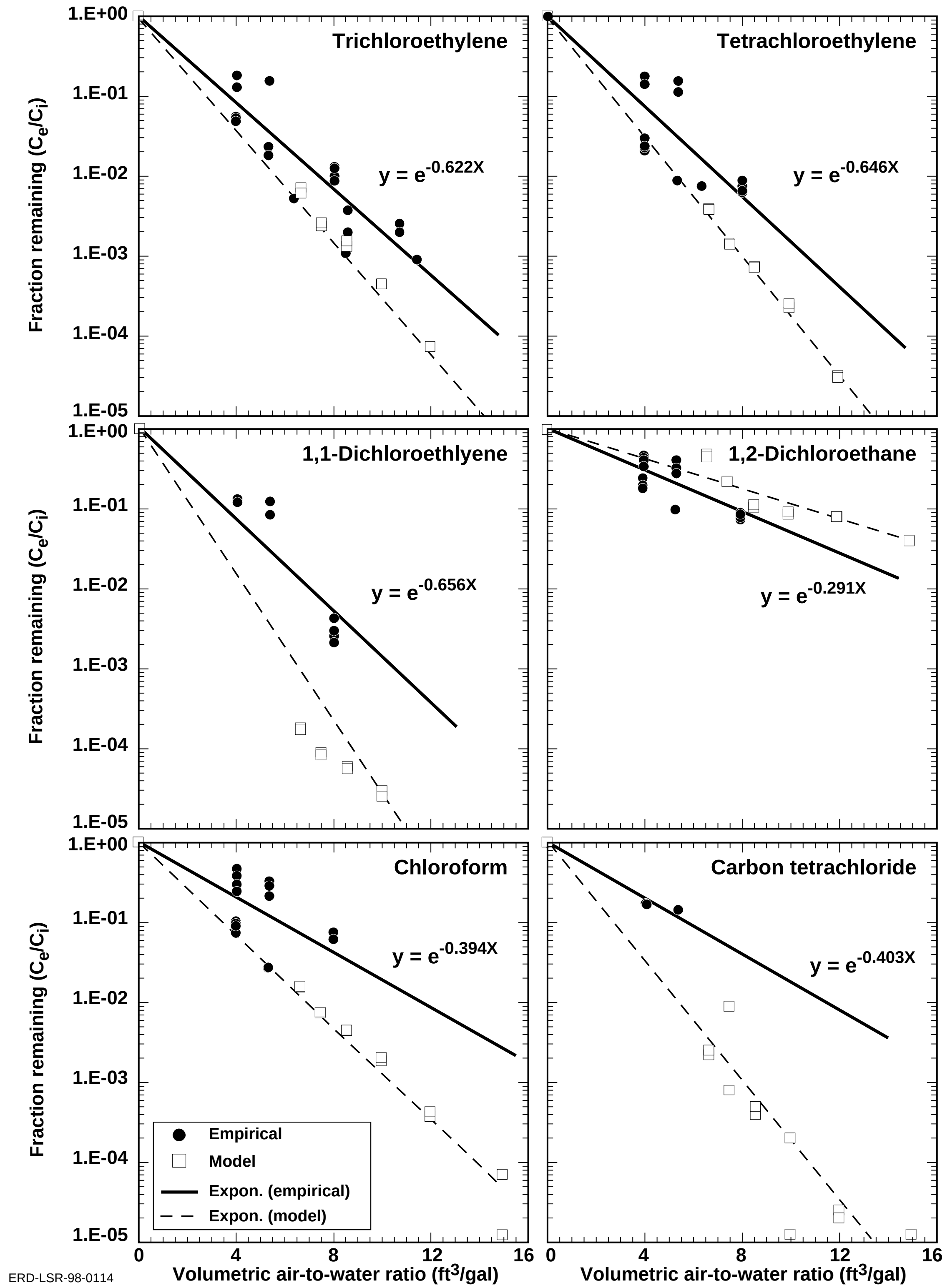

Figure 2. Comparison of field treatability data for six volatile organic compounds to model predictions of a stacked-tray air stripper.

TABLE 4: Predicted Effluent Water Concentration

Location	Air Flow	Volumetric Air-to-Water Ratio	Effluent Water Concentration, μg/L						
	scfm	ft^3/gal	TCE	PCE	1,1-DCE	1,2-DCA	CF	CT	Total
TFC SE	100	16.7	0.00	0.00	0.00	0.01	0.01	0.00	0.03
TFG-1	100	10	0.11	0.00	0.03	0.20	0.14	0.18	0.66
TFE E	200	10.5	0.90	0.16	0.07	0.19	0.18	0.06	1.55
TFD SW	300	10.0	1.74	0.13	0.04	0.27	0.60	0.07	2.85
TF406	150	8.3	0.85	0.04	0.03	0.04	0.07	0.34	1.38
TFD W	150	6.8	2.31	0.01	0.01	0.07	0.09	0.49	2.97
TFD E	300	9.4	1.46	0.09	0.05	0.85	0.22	0.44	3.11
TF518	150	7.5	1.04	0.16	0.07	0.06	0.10	0.49	1.92
TFD SE	150	10.0	0.26	0.35	0.02	0.04	0.05	0.01	0.72
TFD S	150	7.9	2.55	0.06	0.10	0.74	0.02	0.10	3.58
CGSA	150	18.8	0.03	0.00	0.00	0.02	0.02	0.00	0.07

This equation with the empirically derived stripping constants was used to predict effluent water concentration and to determine the required air flow rate for several new extraction locations at LLNL as displayed in Table 4. Effluent water concentrations can also be determined graphically using Figure 2. For example, VOC removal for the "TFD E" location, a recently constructed treatment facility, was found by projecting the volumetric air-to-water ratio (9.4 ft^3/gal) up to the curve-fitted, solid line, and then reading off the corresponding fraction remaining (0.003). Given the influent concentration and the fraction remaining from the graph, the effluent concentration is calculated.

ShallowTray Modeler

North East Environmental Products, Inc. uses its proprietary ShallowTray Modeler software package to select air stripper models for a particular contaminant load (NEEP, 1995). All air stripper models are designed to achieve a constant airflow-rate to tray-surface-area-ratio. The Modeler is based on a single set of empirical data. The user enters the water flow rate and temperature, contaminant type and concentration, and air temperature. The software calculates the effluent concentration for a particular model air stripper with a fixed air flow rate.

To evaluate the accuracy of the ShallowTray Modeler predictions, the test well contaminants and concentrations were entered, and water flow rates were varied to achieve a variety of air-to-water ratios. The results were plotted on a semi-log format and exponentially curve fitted, as displayed in Figure 2.

Conclusion

For all VOCs except 1,2-DCA, the treatment efficiency predicted by the ShallowTray Modeler was more optimistic than actual results obtained in this experiment. The effluent concentrations predicted by the Modeler were approximately 87% lower than the field data based calculations for the eleven locations analyzed.

Of the six chemicals studied, only the CT stripping order based on Henry's constant comparison was different from the empirical results. Because of the low (near detection limit) influent CT concentration, only three detectable effluent concentrations, and hence fraction remaining values, were obtained. Therefore, the CT data should not be considered reliable, and additional data is required to determine if the Modeler accurately predicts CT removal.

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Curriculum Vitae

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