Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Groundwater Cleanup by In-Situ Sparging. XI. Engineered Bioremediation with Aeration Curtains

David J. Wilson[a]; Robert D. Norris[a]
[a] ECKENFELDER INC., NASHVILLE, TENNESSEE, USA

To cite this Article Wilson, David J. and Norris, Robert D.(1997) 'Groundwater Cleanup by In-Situ Sparging. XI. Engineered Bioremediation with Aeration Curtains', Separation Science and Technology, 32: 16, 2569 — 2589
To link to this Article: DOI: 10.1080/01496399708006957
URL: http://dx.doi.org/10.1080/01496399708006957

SEPARATION SCIENCE AND TECHNOLOGY, **32**(16), pp. 2569–2589, 1997

Groundwater Cleanup by In-Situ Sparging. XI. Engineered Bioremediation with Aeration Curtains

DAVID J. WILSON and ROBERT D. NORRIS
ECKENFELDER INC.
227 FRENCH LANDING DRIVE, NASHVILLE, TENNESSEE 37228, USA

ABSTRACT

Mathematical models are developed for two configurations of migration barrier trenches (sparging curtains). The models include removal by air stripping and by biodegradation, and also include the effects of mass transport kinetics of oxygen and of organic contaminant at the bubble–water interface. Air stripping efficiency is rather sensitive to the design of the aeration trench, as observed previously (10); biodegradation efficiency is relatively insensitive to the design. Comparison of results for trichloroethylene (assumed nonbiodegradable) with results for toluene (assumed biodegradable) indicates that the air flow required for toluene is less than one one-hundredth that required for trichloroethylene. The models should be useful for preliminary screening of this technology, for design work, and for performance evaluation. The importance of utilizing the intrinsic bioremediation capacity of the aquifer between the barrier and the point of compliance is discussed.

INTRODUCTION

The remediation of contaminated groundwater is often very long drawn-out because of the very slow rates of diffusion and desorption processes. If contaminants have diffused into porous structures (clay, silt, or till lenses and strata or porous fractured rock), decades or even centuries may be required for them to diffuse back out into advecting groundwater in which they are amenable to treatment or removal (1). As we have come to realize that the rates of such remediations have little to do with the vigor with which water is pumped from the ground, a number of less

intensely engineered remediation techniques, generally in situ and often involving biodegradation processes, have emerged. The National Research Council (1993) (2) examined the circumstances under which in-situ bioremediation is likely to be effective and how this can be demonstrated, and an extensive and rapidly growing literature is developing (3, 4, for example).

One approach which gives promise of reducing long-term costs and providing protection to potential receptors involves the use of migration barriers of various types to limit the growth of the contaminant plume in the aquifer downgradient from the contaminant source. In some instances natural biodegradation alone may be sufficient, and one can rely on intrinsic bioremediation (5, 6). In others, the location of potential receptors, property boundaries, the possibility of inadequate performance of intrinsic bioremediation, etc. may dictate that a lightly engineered solution, such as a migration barrier, be employed. Even in such situations, however, one should not overlook the contribution which can be made by intrinsic bioremediation processes (6, 7).

The most critical requirement for in-situ bioremediation is that an adequate quantity of electron acceptor, usually oxygen, be provided. This must be demonstrated by downgradient monitoring of dissolved oxygen and VOC concentrations. Presently, bioremediation by means of migration barriers is generally carried out in three alternative ways (7).

One way by which oxygen can be provided is by drilling one or more rows of suitably spaced sparging wells so that they intercept the plume, remove some of the VOCs by sparging (physical transfer to the vadose zone), and provide dissolved oxygen for the biodegradation of the remainder. Sparging permits the removal by air stripping of refractory VOCs such as chlorinated organic solvents; in this event the off-gas will require capture and treatment. The application of in-situ air sparging may be limited by the site geology; the presence of low-permeability strata overlying the points of air injection may prevent the use of this technique (8–10, for example).

A second technique for providing oxygen is through the use of oxygen-release compounds such as magnesium peroxide or calcium peroxide. One or more rows of wells are drilled so as to intercept the moving plume, and "socks" filled with oxygen-release compound are lowered into the wells. These socks must be replaced from time to time as the oxygen-release compound is exhausted, typically a period of several months. Maintenance costs are quite low. However, the wells must be placed rather close together, and the oxygen-release compound is relatively expensive. No air stripping is involved, so this approach is effective only

for biodegradable compounds. It also requires no capture of off-gases (7, 11, 12).

A third approach involves the use of aeration trenches, which are excavated at right angles to the direction of movement of the plume and which intercept it. Air is introduced through a horizontal diffuser at the bottom of the trench, which is packed with crushed rock or similar material. Crushed rock should be large enough so that air channeling does not occur (a minimum of 3–4 mm), but not so large that bubble contact times are excessively reduced (13). The groundwater is aerated and air stripped as it moves across the trench; the added dissolved oxygen facilitates biodegradation both within the trench and in the aquifer downgradient from the trench. Calculations modeling the air stripping of VOCs from simple crosscurrent aeration trenches did not indicate a very high level of efficiency (14); however, modeling indicates that relatively minor modifications in trench design result in drastically improved air stripping performance (15).

So-called vacuum-vaporizer wells, developed at Karlsruhe, have been used extensively in Europe, particularly in Germany, and are well adapted for use in forming migration barriers (16, 17, for example). This technique apparently has not seen much use in the United States.

In the following sections we shall first develop equations modeling two configurations of aeration trench (or curtain). The models include air stripping, biodegradation, and mass transport kinetics for VOC and oxygen transport at the water–bubble interfaces. Results are then presented showing how these two configurations respond to variations in the parameters of the models. The paper closes with a brief section on conclusions and recommendations.

ANALYSIS

In this section we develop equations to model two aeration curtain configurations for the removal of dissolved organics by air stripping and/or biodegradation. The first configuration, illustrated schematically in Fig. 1, is a conventional crosscurrent design. The second, shown in Fig. 2, is a crosscurrent/countercurrent design in which the water in the trench is forced to move downward under an impermeable barrier before moving out of the trench. It had been found earlier that such crosscurrent/countercurrent designs show very marked increases in efficiency as compared to the simple crosscurrent configuration (10). In both designs the crushed rock used must be sufficiently large that air channels do not develop, since such channeling would result in markedly decreased mass transport between the gas and aqueous phases. It has been observed that a transition

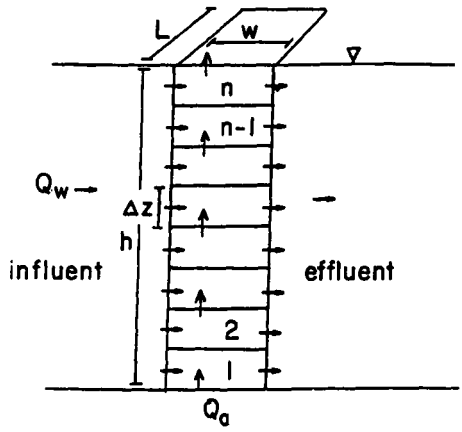

FIG. 1 Schematic diagram of a simple crosscurrent barrier trench. h = depth of water in the trench, w = trench width, z = thickness of a volume element in the trench, Q_w = total water flow through trench, m^3/s, Q_a = total air flow through trench, m^3/s.

from an air channeling regime to a bubble regime takes place as the solid medium particles are increased in size to about 2–3 mm (13). Thus, the porous medium used should be of the order of 4 mm or larger in diameter if channeling is to be avoided. In practice, one would generally carry out lab-scale column experiments to insure absence of channeling and to

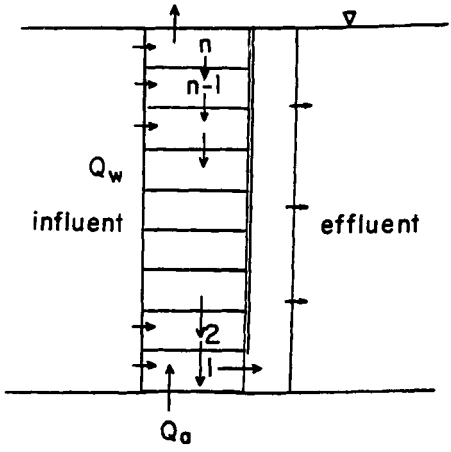

FIG. 2 Schematic diagram of a crosscurrent/countercurrent barrier trench. Notation as in Fig. 1.

determine bubble rise velocities and size with a particular aeration trench packing and air dispersion device. Such experiments would permit one to include such effects as viscosity, medium coarseness and porosity, surface tension, etc. on mass transport without the need for carrying out difficult calculations in multiphasic flow.

We first examine the simple crosscurrent configuration. Geometry and much of the notation are indicated in Fig. 1. Definitions of symbols used are given in Table 1.

We assume for simplicity that the gas phase is incompressible. Then the bubble contact time in a single volume element, ΔV, is given by

TABLE 1
Notation

Q_w	water flow, m^3/s
Q_a	air flow, m^3/s
L	length of trench, m
w	width of trench, m
h	height of trench, m
ν	porosity of trench packing, dimensionless
n	number of volume elements into which trench is partitioned
Δz	thickness of a volume element, m
ΔV	hLw/n = volume of a volume element, m^3
ΔV_a	volume of air in a volume element
v_b	bubble rise velocity, m/s
r_b	bubble radius, m
K_c	Henry's constant of contaminant, dimensionless
λ_c	mass transfer rate constant of contaminant, m/s
K_o	Henry's constant of oxygen, dimensionless
λ_o	mass transfer rate constant of oxygen, m/s
C_{infl}^{cw}	influent contaminant concentration, kg/m^3
C_{infl}^{ow}	influent oxygen concentration, kg/m^3
C_i^{cw}	aqueous contaminant concentration in ith volume element, kg/m^3
C_i^{ca}	vapor-phase contaminant concentration in ith volume element, kg/m^3
C_i^{oa}	vapor-phase oxygen concentration in ith volume element, kg/m^3
C_i^{ow}	aqueous oxygen concentration in ith volume element, kg/m^3
C_{eff}^{cw}	average effluent contaminant concentration, kg/m^3
C_{eff}^{ow}	average effluent oxygen concentration, kg/m^3
B_i	biomass concentration, kg/m^3 of bulk medium
K_u	maximum rate of biomass formation, $kg/m^3 \cdot s$
$C_{1/2}$	substrate constant in Monod expression, kg/m^3
$O_{1/2}$	oxygen constant in Monod expression, kg/m^3
k_{die}	die-off rate constant for microorganisms, s^{-1}
n_c	mass of substrate required per unit mass of biomass formed
n_o	mass of oxygen required per unit mass of biomass formed
dt	time increment in numerical integration, s

$$\tau = \Delta z / v_b \tag{1}$$

The volume of air in a single volume element is

$$V_a = Q_a \tau \tag{2}$$

and the volume of water in a volume element is

$$\Delta V_w = \Delta V - \Delta V_a \tag{3}$$

Making the steady-state assumption for contaminant in the gas phase then yields the following mass balance equation for contaminant in the aqueous phase of the ith volume element.

$$\Delta V_w \frac{dC_i^{cw}}{dt} = (Q_w/n)(C_{infl}^{cw} - C^{cw}) + Q_a(C_{i-1}^{ca} - C_i^{ca}) - \Delta V_w n_c \frac{\partial B_i}{\partial t} \tag{4}$$

where $C_0^{ca} = 0$. In similar fashion the mass balance equation for oxygen in the aqueous phase of the ith volume element is

$$\Delta V_w \frac{dC_i^{ow}}{dt} = (Q_w/n)(C_{infl}^{ow} - C_i^{ow}) + Q_a(C_{i-1}^{oa} - C_i^{oa}) - \Delta V_w n_o \frac{\partial B_i}{\partial t} \tag{5}$$

Here C_0^{oa} is the concentration of oxygen (kg/m^3) in the injected air.

The rate of production of biomass is assumed to be given by a Monod-type expression,

$$\frac{\partial B_i}{\partial t} = K_u \frac{C_i^{cw}}{C_{1/2} + C_i^{cw}} \frac{C_i^{ow}}{O_{1/2} + C_i^{ow}} B_i \tag{6}$$

To this we adjoin a die-off term to get Eq. (7) for the net rate of formation of biomass.

$$\frac{dB_i}{dt} = \frac{\partial B_i}{\partial t} - k_{die} B_i \tag{7}$$

Both K_u and k_{die} will be affected by such factors as the characteristics of the support (typically crushed rock) in the trench.

The vapor-phase contaminant and oxygen concentrations are calculated as follows. Let $C_B(t)$ be the contaminant concentration in the bubble in the time period during which it transits the ith volume element. Then

$$\frac{4\pi r_b^3}{3} \frac{dC_B}{dt} = 4\pi r_b^2 \lambda_c (K_c C_i^{cw} - C_B) \tag{8}$$

Integration of this equation from 0 to τ then yields

$$\exp[(3\lambda_c/r_b)\tau] C_B(\tau) - C_B(0) = K_c C_i^{cw} \{\exp[(3\lambda_c/r_b)\tau] - 1\} \tag{9}$$

where we have assumed that C_i^{cw} can be regarded as being constant over

the time interval $(0, \tau)$. Note that $C_B(0) = C_{i-1}^{ca}$ and $C_B(\tau) = C_i^{ca}$. Then

$$C_i^{ca} = C_{i-1}^{ca}\exp[-(3\lambda_c/r_b)\tau] + K_c C_i^{cw}\{1 - \exp[-(3\lambda_c/r_b)\tau]\} \quad (10)$$

Given that $C_0^{ca} = 0$ and that the C_i^{cw} are given for the time interval $(0, \tau)$, one can then calculate the C_i^{ca} recursively.

The gas-phase oxygen concentrations C_i^{oa} are calculated in exactly similar fashion; the result is

$$C_i^{oa} = C_{i-1}^{oa}\exp[-(3\lambda_o/r_b)\tau] + K_o C_i^{ow}\{1 - \exp[-(3\lambda_o/r_b)\tau]\} \quad (11)$$

As before, given that the value of C_0^{oa} is known (atmospheric oxygen concentration) and that the C_i^{ow} are given for the time interval $(0, \tau)$, the C_i^{oa} can be calculated recursively.

The modeling equations are then Eqs. (6), (7), (10), (11), (12), and (13). Equations (12) and (13) are obtained from Eqs. (4) and (5).

$$\frac{dC_i^{cw}}{dt} = \frac{1}{\Delta V_w}\left[\frac{Q_w}{n}(C_{infl}^{cw} - C_i^{cw}) + Q_a(C_{i-1}^{ca} - C_i^{ca})\right] - n_c\frac{\partial B_i}{\partial t} \quad (12)$$

$$\frac{dC_i^{ow}}{dt} = \frac{1}{\Delta V_w}\left[\frac{Q_w}{n}(C_{infl}^{ow} - C_i^{ow}) + Q_a(C_{i-1}^{oa} - C_i^{oa})\right] - n_o\frac{\partial B_i}{\partial t} \quad (13)$$

The average contaminant concentration in the water immediately downgradient of the trench is then given by

$$\langle C_{effl}^{cw}\rangle = \sum_{i=1}^{n} C_i^{cw}/n \quad (14)$$

The average aqueous oxygen concentration immediately downgradient of the trench is

$$\langle C_{effl}^{ow}\rangle = \sum_{i=1}^{n} C_i^{ow}/n \quad (15)$$

The contaminant concentration in the off-gas discharged from the trench is just C_n^{ca}. This figure will be needed to ascertain whether or not some form of off-gas treatment will be needed. This treatment might be simply use of the vadose zone soil overlying the water-filled trench as a bioreactor if the contaminants are readily biodegradable.

We next turn to the crosscurrent/countercurrent configuration diagrammed in Fig. 2. The analysis is very similar to that needed for the simple crosscurrent model analyzed above. The water flow is changed, however, so the terms describing advective transport of contaminant or

oxygen in the aqueous phase (i.e., those terms multiplied by Q_w in Eqs. 12 and 13 must be modified. For this second configuration the aqueous advective terms are

$$\left[\frac{\partial C_i^{xw}}{\partial t}\right]_{adv} = (Q_w/n)\{C_{infl}^{xw} + (n - i)C_{i+1}^{xw} - (n - i + 1)C_i^{xw}\} \quad (16)$$

where x = c (contaminant) or o (oxygen).

The aqueous contaminant and oxygen concentrations in the effluent from the aeration section of the trench are given by C_1^{cwa} and C_1^{ow}, respectively. The contaminant concentration in the off-gas discharged from the trench is given by C_n^{ca}.

In evaluating the results described in the next section, one must keep in mind that it is neither necessary or desirable to reduce the contaminant concentration to the vanishing point immediately downgradient of the sparging trench if the contaminant is biodegradable. The dissolved oxygen concentration of the trench effluent should, however, be sufficient to provide enough electron acceptor to permit complete degradation of the residual contaminants by the mechanisms involved in intrinsic bioremediation processes. This should be complete some distance upgradient from the point of compliance.

RESULTS

We first examine the air stripping of TCE by aeration curtains (trenches) without any biodegradation. Default parameters for these runs are given in Table 2. Parameters describing mass transport of oxygen and VOC

TABLE 2
Default Parameters for Air Stripping of TCE by Means of an Aeration Curtain

Depth of trench	3 m
Length of trench	20 m
Width of trench	1 m
Number of volume elements assumed	4
Porosity of trench packing	0.5
Superficial velocity of groundwater	0.1 m/day
Volumetric flow of groundwater through curtain	6.94×10^{-5} m^3/s
Air flow rate	Specified in Table 3
Temperature	15°C
VOC	Trichloroethylene
Henry's constant of VOC	0.2821
Mass transport rate constant of VOC	1×10^{-5} m/s
Influent VOC concentration	10 mg/L

(bubble size and transit time, mass transport coefficient) depend critically on the characteristics of the porous medium and the air dispersion system; the values used here are for illustrative purposes only.

The calculations summarized in Table 3 simulate the air stripping of TCE from groundwater with a superficial velocity of 0.1 m/day and at 15°C by an aeration curtain 3 m deep by 20 m wide; the dependence of the percent removal on the air flow rate (standard cubic feet per minute) for the simple crosscurrent aeration curtain and for the crosscurrent/countercurrent curtain is given. The bubble rise velocity is 10 cm/s, the bubble diameter is 1 mm, and the mass transport rate constants for TCE and oxygen are 1×10^{-5} m/s. For this system it is necessary to use an air flow rate of 100 SCFM to achieve 99+% removal of the TCE if the simple crosscurrent aeration configuration is used, and 50 SCFM to achieve 99+% removal if the crosscurrent/countercurrent configuration is used. For all gas flow rates the crosscurrent/countercurrent configuration removes somewhat more TCE than does the simple crosscurrent configuration. In either case the off-gas must be collected and treated, since the TCE is not being biodegraded.

Table 4 summarizes the TCE removal efficiencies of similar curtains for which the bubble diameter is 0.5 mm and the bubble rise velocity is 5 cm/s; other parameters are as in Table 2. The larger surface-to-volume ratio of the bubbles and their longer contact time result in water-to-air mass transport of TCE to be significantly faster, which in turn results in higher TCE removal efficiencies at any given flow rate. As before, the

TABLE 3
Percent TCE Removal by Crosscurrent and Crosscurrent/Countercurrent Aeration Curtains (bubble diameter = 1 mm, bubble rise velocity = 10 cm/s; other parameters as in Table 2)

Air flow rate (SCFM)	Percent TCE removal	
	Crosscurrent	Crosscurrent/countercurrent
100	99.45	99.64
50	98.90	99.28
25	97.82	98.56
10	94.72	96.40
5	89.94	92.83
2.5	81.62	85.95
1	63.62	68.57

TABLE 4
Percent TCE Removal by Crosscurrent and Crosscurrent/Countercurrent Aeration Curtains (bubble diameter = 0.5 mm, bubble rise velocity = 5 cm/s; other parameters as in Table 2)

Air flow rate (SCFM)	Percent TCE removal	
	Crosscurrent	Crosscurrent/ countercurrent
100	99.65	99.84
50	99.30	99.69
25	98.61	99.37
10	96.58	98.40
5	93.35	96.74
2.5	87.41	93.24
1	72.93	82.09

crosscurrent/countercurrent configuration outperforms the simple crosscurrent aeration curtain design.

Table 5 presents TCE removal efficiencies for curtains for which the mass transport rate constant has been increased tenfold, to 1×10^{-4} m/s, the bubble diameter is 0.5 mm, and the bubble rise velocity is 5 cm/s.

TABLE 5
Percent TCE Removal by Crosscurrent and Crosscurrent/Countercurrent Aeration curtains (bubble diameter = 0.5 mm, bubble rise velocity = 5 cm/s, mass transport rate constant of VOC = 1×10^{-4} m/s; other parameters as in Table 2)

Air flow rate (SCFM)	Percent TCE removal	
	Crosscurrent	Crosscurrent/ countercurrent
100	99.68	99.87
50	99.35	99.74
25	98.71	99.47
10	96.82	98.66
5	93.81	97.26
2.5	88.21	94.28
1	74.30	84.36

The results indicate modest increases in removal efficiencies over those given in Table 4. Evidently air-water mass transport of TCE is not a seriously limiting factor for these runs.

The increased efficiency of the crosscurrent/countercurrent design as compared to the simple crosscurrent system suggests that the capital expense of installing the vertical barrier in the cross-current/countercurrent system might well result in significant savings in operating costs, in that the volume of off-gas requiring treatment during the lifetime of the project could be reduced by about 50%.

We next model the air stripping/biodegradation of toluene by aeration trenches. Default parameters are given in Table 6. The biological parameters used were those selected for our earlier work (19) in which the values selected are compared with those used by previous investigators. These parameters can be expected to be quite site-specific, so our results should be regarded as order-of-magnitude, indicating trends and qualitative behavior, rather than as giving precise numerical values.

TABLE 6
Default Parameters for Air Stripping/Biodegradation of Toluene by Means of an Aeration Curtain

Depth of trench	3 m
Length of trench	20 m
Width of trench	1 m
Number of volume elements assumed	4
Porosity of trench packing	0.5
Bubble diameter	1 mm
Bubble rise velocity	10 cm/s
Superficial velocity of groundwater	0.1 m/day
Volumetric flow of groundwater through curtain	6.94×10^{-5} m^3/s
Air flow rate	Specified in Tables 7 and 8
Temperature	15°C
VOC	Toluene
Henry's constant of VOC	0.2081
Mass transport rate constant of VOC	1×10^{-5} m/s
Henry's constant of oxygen	29.1
Mass transport rate constant of oxygen	1×10^{-5} m/s
K_u, rate constant for biomass formation	2×10^{-5} s^{-1}
$C_{1/2}$, substrate constant in Monod expression	0.5 mg/L
$O_{1/2}$, oxygen constant in Monod expression	0.1 mg/L
Mass substrate required per unit biomass formed	2.0
Mass oxygen required per unit biomass formed	7.06
Influent toluene concentration	10 mg/L
Influent oxygen concentration	0 mg/L
Initial biomass concentration in trench	1 mg/L

Table 7 gives the percent toluene removal by crosscurrent and by crosscurrent/countercurrent aeration curtains at various air-flow rates after 50 days of operation. Other parameters are given in Table 6. In Table 8 the bubble diameter has been decreased to 0.5 mm, the bubble rise velocity has been decreased to 5 cm/s, and the mass transfer rate constants have been increased to 1×10^{-4} m/s. In all cases the air flow required to achieve virtually complete removal of the toluene is very much smaller than that required to achieve a corresponding level of removal of TCE by air stripping alone. Gas-flow rates of 0.05 SCFM are adequate to remove more than 99% of the toluene in all cases. If mass transport is rapid (Table 8), the crosscurrent/countercurrent aeration trench requires only 0.02 SCFM to achieve 99+% removal of the toluene, virtually all of which is destroyed by biodegradation. At air-flow rates of 0.05 SCFM or more the water downgradient of both curtain configurations contains 6 mg/L or more of dissolved oxygen. This oxygen is available to degrade biodegradable organics diffusing from the soil matrix downgradient from the curtain, although other electron acceptors may contribute as well.

The results of Tables 7 and 8 indicate that the crosscurrent/countercurrent configuration is slightly more efficient than the simple crosscurrent design, but in all cases in which the air flow is above 0.05 SCFM the removal efficiency and the dissolved oxygen residual are sufficient that one would probably not bother with the added expense of the crosscurrent/countercurrent design here. If the air flow is above 0.05 SCFM, the oxygen

TABLE 7
Percent Toluene Removal by Crosscurrent and Crosscurrent/Countercurrent Aeration Curtains with Biodegradation (parameters as in Table 6)

Air flow rate (SCFM)	Percent toluene removal after 50 days' operation	
	Crosscurrent	Crosscurrent/countercurrent
10	99.78	99.78
1	99.78	99.78
0.1	99.78	99.78
0.05	99.78	99.78
0.025	93.56	99.78
0.02	81.35	88.02
0.015	64.69	66.25
0.01	44.22	44.31

TABLE 8
Percent Toluene Removal by Crosscurrent and Crosscurrent/Countercurrent Aeration Curtains with Biodegradation (bubble diameter = 0.5 mm, bubble rise velocity = 5 cm/s, mass transfer rate constants = 1×10^{-4} m/s; other parameters as in Table 6)

	Percent toluene removal after 50 days' operation	
Air flow rate (SCFM)	Crosscurrent	Crosscurrent/ countercurrent
0.05	99.78	99.78
0.025	99.78	99.78
0.02	95.66	99.78
0.015	74.10	80.11
0.01	50.45	53.51

concentration in the off-gas is more than sufficient to permit degradation of the quite small concentrations of toluene vapor which are present.

An air stripping barrier trench (no biodegradation) under normal operation reaches a steady state relatively quickly. For example, the run at 10 SCFM shown in Table 3 achieved steady-state operation after just under 3 days of operation. In marked contrast, the runs in Tables 7 and 8, in which toluene is being biodegraded, had not achieved true steady-state operation after 50 days. The long time periods during which transient behavior is observed are due to the slow rate of growth of biomass. The time evolution of a crosscurrent/countercurrent aeration trench in which toluene is being removed by air stripping and biodegradation at an air-flow rate of 0.05 SCFM is shown in Figs. 3–6. Parameters are as in Table 6.

Figure 3 shows an initial rapid rate of decrease of the effluent toluene concentration by aeration and the biomass initially present. This takes place during the first 3 days or so of the run, and is followed by a much slower decrease in effluent toluene concentration which is still continuing, although quite slowly, after 50 days of operation.

The effluent dissolved-oxygen concentration, plotted versus time in Fig. 4, rises to essentially its final value in about 4 days. The D.O. level achieved after 4 days is far more than that which would be required to degrade the very low residual toluene concentration in the effluent. During the first couple of days of operation, however, one might be quite con-

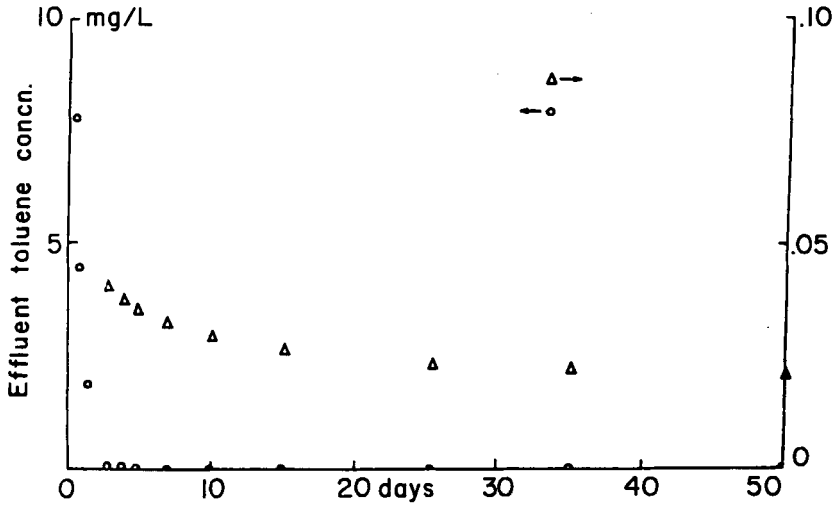

FIG. 3 Toluene removal by bioremediation; plots of effluent toluene concentration (note two scales) versus time. Crosscurrent/countercurrent configuration. Air flow rate = 0.05 SCFM; other parameters as in Table 6.

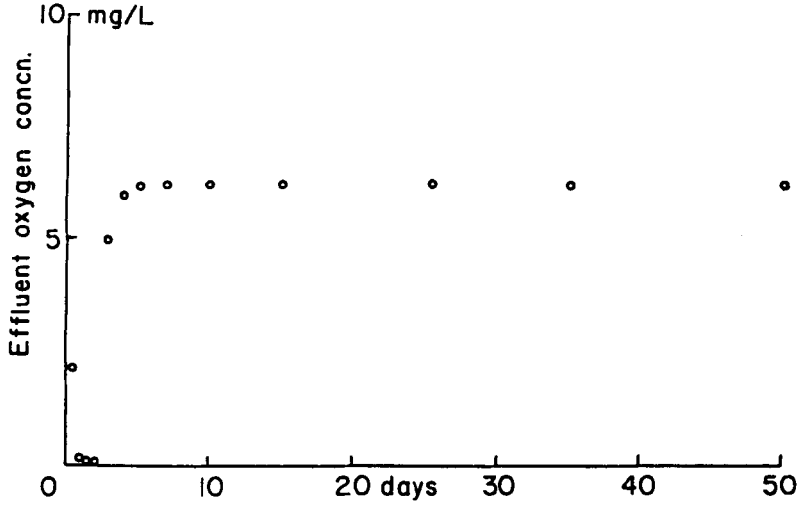

FIG. 4 Toluene removal by bioremediation; plot of effluent dissolved oxygen concentration versus time. Crosscurrent/countercurrent configuration. Parameters as in Fig. 3.

cerned to see essentially anoxic water being discharged downgradient from the barrier trench.

Figure 5 plots the concentration of toluene in the off-gas from the barrier trench versus time. The high toluene concentrations observed initially (nearly 1500 mg/m^3) rapidly decrease during the first 5 to 6 days of operation to a value of about 6 mg/m^3, and then slowly decrease down to about 4 mg/m^3 after 50 days of operation. The concentration of oxygen in the off-gas, plotted versus time in Fig. 6, is far in excess of that required to degrade this toluene as the off-gas moves up through the overlying vadose zone, indicating that one could easily operate at a substantially lower gas-flow rate. The off-gas oxygen concentration has achieved its final value after about 5 days.

The time evolution of a simple crosscurrent aeration trench in which toluene is being removed by air stripping and biodegradation at an air-flow rate of 0.05 SCFM is shown in Figs. 7–10. Parameters are as in Table 6.

The most obvious point to be noted on comparison of Figs. 3–6 with Figs. 7–10 is how minor are the differences in behavior which occur with these two configurations which have very different water-flow patterns. This is in marked contrast to the differences in behavior between different

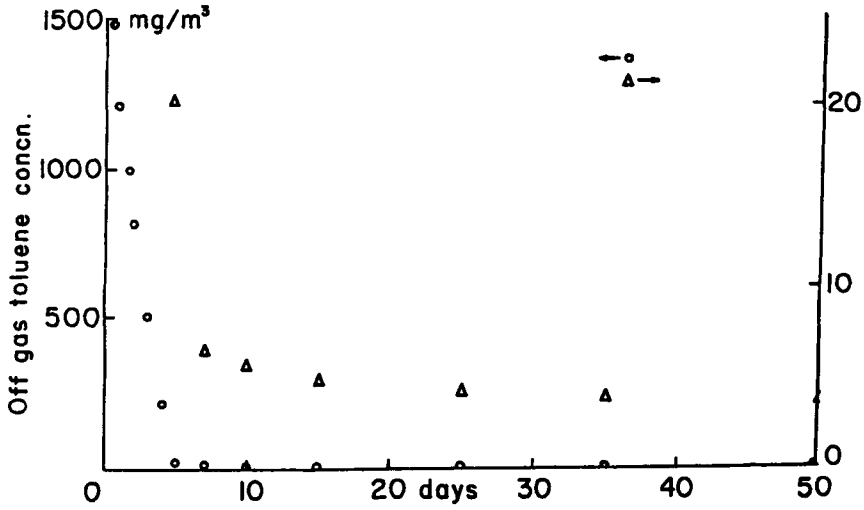

FIG. 5 Toluene removal by bioremediation; plots of off-gas toluene concentration (two scales) versus time. Crosscurrent/countercurrent configuration. Parameters as in Fig. 3.

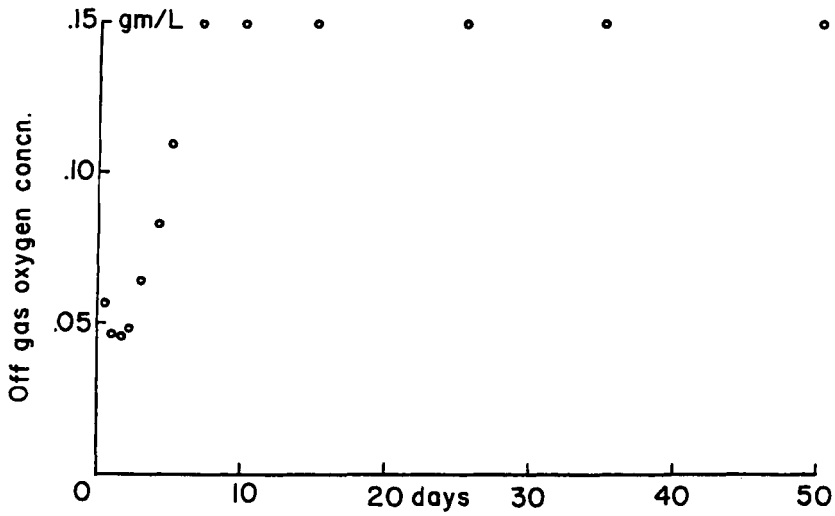

FIG. 6 Toluene removal by bioremediation; plot of off-gas oxygen concentration versus time. Crosscurrent/countercurrent configuration. Parameters as in Fig. 3.

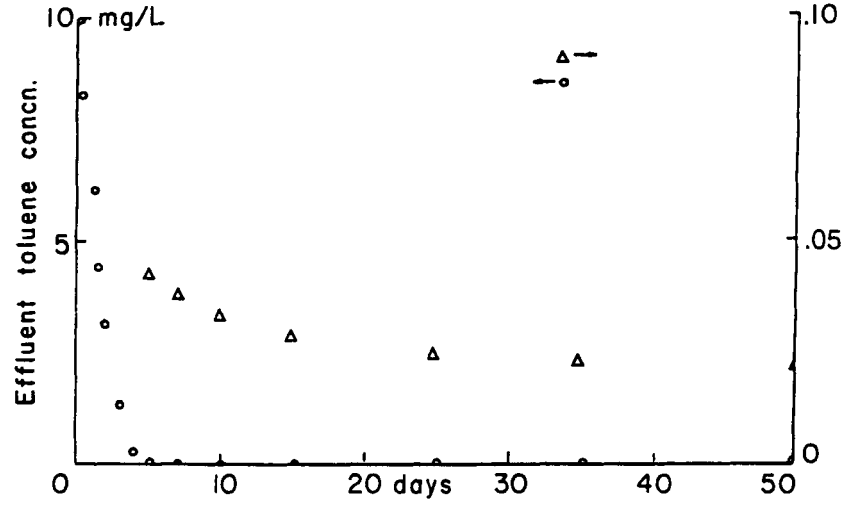

FIG. 7 Toluene removal by bioremediation; plots of effluent toluene concentration (note two scales) versus time. Crosscurrent configuration. Parameters as in Fig. 3.

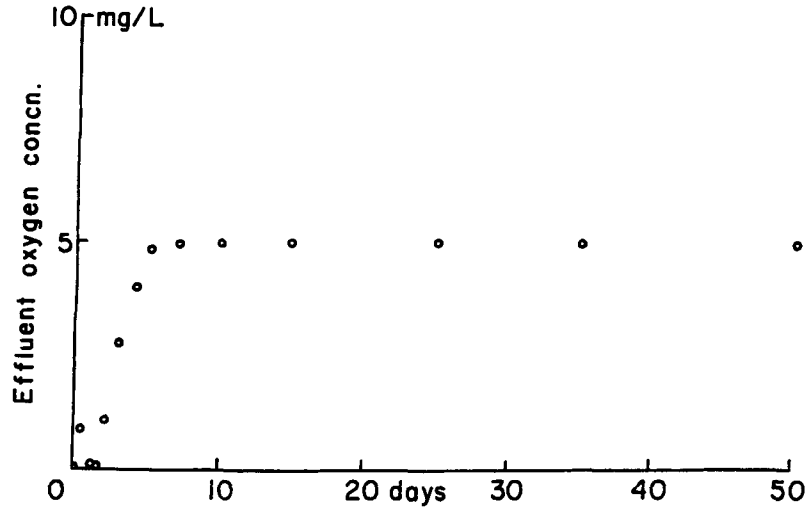

FIG. 8 Toluene removal by bioremediation; plot of effluent dissolved oxygen concentration versus time. Crosscurrent configuration. Parameters as in Fig. 3.

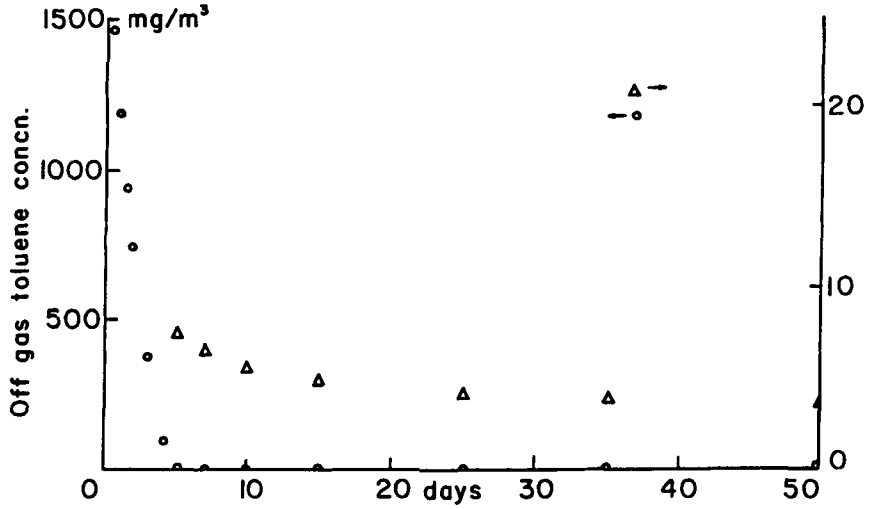

FIG. 9 Toluene removal by bioremediation; plots of off-gas toluene concentration (two scales) versus time. Crosscurrent configuration. Parameters as in Fig. 3.

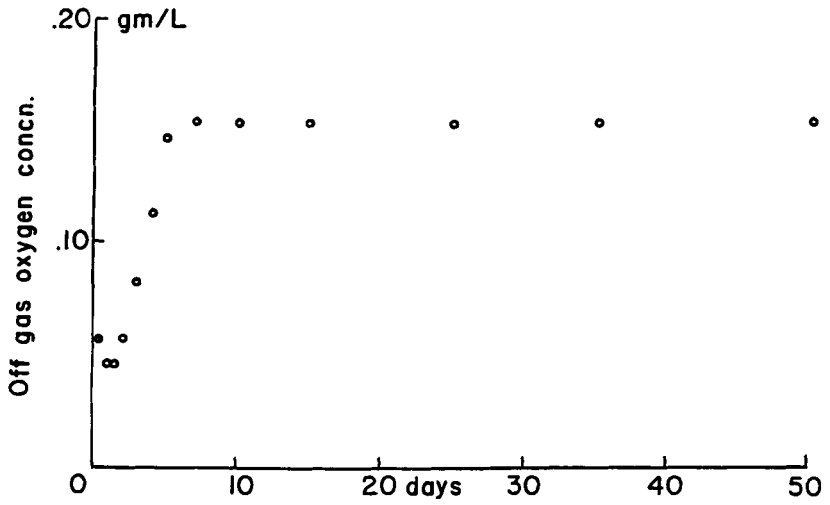

FIG. 10 Toluene removal by bioremediation; plot of off-gas oxygen concentration versus time Crosscurrent configuration. Parameters as in Fig. 3.

aeration curtain configurations used for simple air stripping (14). In both configurations virtually all of the VOC is biodegraded.

Comparison of Fig. 3 with Fig. 7 shows that the initial rate of decrease in effluent toluene concentration is somewhat larger in the crosscurrent/countercurrent system; after 5 days, however, the two plots are very similar. Examination of Figs. 4 and 8 indicates that both systems achieve essentially steady-state effluent dissolved oxygen concentrations within 5 days, with effluent D.O. levels in the crosscurrent/countercurrent system of 6.2 mg/L and in the crosscurrent system of 4.9 mg/L.

Figures 5 and 9 show that the off-gas toluene concentrations for the two systems show virtually identical behavior; in both cases high initial values drop to extremely low levels in about 5 days. Similarly, the plots shown in Figs. 6 and 10 indicate that the off-gas oxygen concentrations for the two systems show very similar behavior; that for the simple crosscurrent system is slightly larger. (Note the difference in vertical scale of the two figures.)

CONCLUSIONS AND RECOMMENDATIONS

First, we note that the values of many of the parameters in bioremediation models are highly site and compound specific, so the results of the

modeling exercises described here should not be interpreted too literally. The models should be helpful in visualizing in a semiquantitative way what is happening, identifying critical parameters, predicting trends of removal efficiency as parameters are changed, and comparing trench configurations.

- The most outstanding point to be noted from these results is the enormous difference between the relatively large quantity of air required for air stripping without biodegradation and the very small quantity required when a readily biodegradable contaminant is being removed.
- The results obtained here indicate that air stripping by a crosscurrent/countercurrent barrier trench is more efficient than air stripping by a simple crosscurrent trench, in agreement with our earlier results (13). However, the difference in biodegradation efficiency between the two configurations is much less, and would probably not warrant the additional expense of the crosscurrent/countercurrent design if only biodegradable contaminants were present. If one is dealing with a mixture of toluene and TCE and is destroying the TCE by cometabolism, one would expect there to be little difference between the performances of the two configurations.
- If the barrier trench is operated at an air flow that is sufficient to provide a substantial dissolved oxygen concentration in the effluent downgradient, one may be able to enhance intrinsic bioremediation processes in that portion of the aquifer between the barrier trench and the point of compliance.
- Biological processes are sufficiently slow that rather extended periods of time may be required for bioremediation by means of a barrier trench to achieve full effectiveness. Air stripping trenches, on the other hand, reach steady-state operation substantially more quickly.
- Off-gas treatment costs in connection with air stripping may be rather substantial owing to the comparatively large quantity of off-gas involved. Off-gas treatment should not be required with a properly designed and operated biological barrier trench, since the overwhelming bulk of the contaminant is biodegraded in the trench, in the overlying vadose zone, or in the aquifer immediately downgradient from the trench.
- If one is treating a contaminated groundwater plume which contains both biodegradable and refractory VOCs, one would probably consider use of one of the two crosscurrent/countercurrent barrier trench designs discussed earlier (13). These provide substantially more efficient air stripping than does the simple crosscurrent design, so that lower air-flow rates could be used. This, in turn, reduces off-gas treatment

costs. The results presented here indicate that such designs are not expected to show poorer bioremediation performance than the simple crosscurrent design. This evaluation, however, is complicated by the fact that toluene or other aerobically degradable organics may play a role in the aerobic and/or anaerobic degradation of some chlorinated compounds such as TCE.

REFERENCES

1. Committee on Groundwater Cleanup Alternatives, *Alternatives for Groundwater Cleanup*, National Academy Press, Washington, D.C., 1994.
2. National Research Council, *In Situ Bioremediation. When Does It Work?*, National Academy Press, Washington, D.C., 1993.
3. R. E. Hoeppel and R. E. Hinchee, "Enhanced Biodegradation for On-Site Remediation of Contaminated Soils and Groundwater," in *Hazardous Waste Site Soil Remediation: Theory and Application of Innovative Technologies* (D. J. Wilson and A. N. Clarke, Eds.), Dekker, New York, NY, 1994, Chapter 7.
4. R. E. Hinchee, R. N. Miller, and P. C. Johnson (Eds.), *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes*, Battelle Press, Columbus, OH, 1995.
5. R. E. Hinchee, J. T. Wilson, and D. C. Downey (Eds.), *Intrinsic Bioremediation*. Battelle Press, Columbus, OH, 1995.
6. T. H. Wiedemeier, J. T. Wilson, D. H. Kampbell, R. N. Miller, and J. E. Hansen, *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater*, Air Force Center for Environmental Excellence, Technology Transfer Division, Brooks Air Force Base, San Antonio, TX, 1995.
7. J. Armstrong and R. D. Norris, *The Use of Migration Barriers to Prevent the Spread of Petroleum Hydrocarbons*, HazMat International Conference, Philadelphia, PA, June 14–16, 1995.
8. R. A. Brown and R. Fraxedas, "Air Sparging—Extending Volatilization to Contaminated Aquifers," *Proceedings, Symposium on Soil Venting*, Robert S. Kerr Environmental Research Laboratory, Houston, TX, April 29–May 1, 1991.
9. R. A. Brown and F. Jasiulewicz, "Air Sparging: A New Model for Remediation," *Pollut. Eng.*, *24*(13), 52 (July 1, 1992).
10. M. C. Marley, D. J. Hazebrouk, and M. T. Walsh, "The Application of In-Situ Air Sparging as an Innovative Soil and Groundwater Technology," *Ground Water Monit. Rev.*, p. 137 (Spring 1992).
11. G. C. Bianchi-Mosquera, R. M. Allen-King, and D. D. Mackay, "Enhanced Degradation of Dissolved Benzene and Toluene Using a Solid Oxygen-Releasing Compound," *Ibid.*, p. 120 (1994).
12. C. M. Kao and R. C. Borden, "Enhanced Aerobic Bioremediation of a Gasoline Contaminated Aquifer by Oxygen-Releasing Barriers", in *Hydrocarbon Bioremediation*, Lewis Publishers, Boca Raton, FL, 1994.
13. M. C. Brooks, W. R. Wise, and M. D. Annable, "Two-Phase Flow Patterns in Porous Media: An Investigation Relating to In-Situ Air Sparging," in *Proceedings, 1st International Symposium on In Situ Air Sparging for Site Remediation, October 24–25, 1996, Las Vegas, Nevada*; International Network for Environmental Training, Inc., 7508 Masters Dr., Potomac, MD 20854.

14. D. J. Wilson, S. Kayano, R. D. Mutch, and A. N. Clarke, "Groundwater Cleanup by In Situ Sparging. I. Mathematical Modeling," *Sep. Sci. Technol.*, *27*, 1023 (1992).
15. D. J. Wilson, R. D. Mutch, and R. D. Norris, "Groundwater Cleanup by In-Situ Aeration. XII. An Improved Aeration Curtain Design," Submitted for Publication.
16. B. Herrling and W. Buermann, "A New Method for In-Situ Remediation of Volatile Contaminants in Groundwater—Numerical Simulation of the Flow Regime," in *Proceedings, 8th International Conference on Computational Methods in Water Resources*, Venice, Italy, June 1990.
17. B. Herrling, J. Stamm, E. J. Alesi, P. Brinnel, F. Hirschberger, and M. R. Sick, *In Situ Groundwater Remediation of Strippable Contaminants by Vacuum Vaporizer Wells (UVB): Operation of the Well and Report about Cleaned Industrial Sites*, Presented at the 3rd Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Dallas, TX, June 11–13, 1991.
18. K. Rutherford, D. H. Bass, W. McPhee, and P. C. Johnson, "Estimation of Oxygen Mass Transfer Coefficients during Air Sparging," in *Proceedings, 1st International Symposium on In Situ Air Sparging for Site Remediation, October 24–25, 1996, Las Vegas, Nevada*; International Network for Environmental Training, Inc., 7508 Masters Dr., Potomac, MD 20854.
19. C. Gomez-Lahoz, J. M. Rodriguez-Maroto, and D. J. Wilson, 1994, "Biodegradation Phenomena during Soil Vapor Extraction: A High-Speed Nonequilibrium Model," *Sep. Sci. Technol.*, *29*, 429 (1994).

Received by editor July 3, 1996
Revision received November 1996