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# Groundwater Cleanup by In-Situ Sparging. XII. An Improved Aeration Curtain Design

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## ABSTRACT

The performances of three designs of aeration curtains are modeled mathematically, and the results of model computations are used to compare the efficiencies of the designs. The efficiency of the standard crosscurrent design for trichloroethylene (TCE) removal is found to be substantially less than that of a crosscurrent/countercurrent design in which a vertical barrier in the curtain causes flow of the water countercurrent to that of the air. This design, in turn, is less efficient than a design in which the bottom section of the curtain is operated in a purely countercurrent mode. Model calculations indicate that this last design is readily able to achieve removals of volatile organic compounds such as TCE of better than 99%. The implications of the three designs for bioremediation are explored; all provide satisfactory oxygen transfer. Aspects of construction and implementation are discussed.

## I. INTRODUCTION

The removal or biodegradation of volatile organic compounds (VOCs) from contaminated aquifers by various air sparging techniques has achieved wide acceptance and established a good track record (1, 2). A substantial portion of a recent conference on innovative technologies was devoted to air sparging, the proceedings of which (3) provide an excellent overview of the current state-of-the-art.

Several of these papers (4–8) raised several questions about the dynamics of water movement near a standard sparging well (simple air injection into the aquifer, usually with a soil vapor extraction system collecting

VOCs in the vadose zone). The conclusions of interest here are the following. (1) Steady-flow injection of air into an aquifer via a standard sparging well results in little circulation of water in the domain of influence of the well, and (2) the injected air moves to the top of the aquifer in persistent channels, rather than as isolated bubbles.

The implications of these facts for the efficiency of mass transfer rates in sparging are not good. Pulsed operation of the wells was suggested as a possible mitigating technique. Mixing during sparging and biosparging has been discussed in some detail by Clayton et al. (9).

We have modeled this for the sparging (with air channeling) of dissolved VOCs (10) and DNAPL (11) and for the biosparging of NAPL and dissolved VOC (12). In agreement with experimental results (5, 8), large increases in removal and biodegradation rates were observed as the dispersivity was increased, made possible by pulsing of the air injection well(s).

A more elaborate well configuration has been used in Germany, the UVB or vacuum-vaporizer well, pioneered by Herrling and his collaborators (13). In this, water is drawn into a large-bore well through a screened section near the bottom of the aquifer, air stripped, and pumped back into the aquifer through a screened section just below the water table. The UVB technique has been used at 80 sites in Europe, and is in use at 22 sites in the United States (14).

A third configuration for sparging is that of an aeration curtain (15). This is a trench oriented at right angles to the direction of groundwater flow and located so as to intercept a plume of contaminated groundwater and remediate it as the groundwater passes across the curtain. A standard design has been to place a horizontal slotted pipe at the bottom of the trench, to fill the trench with gravel or crushed rock to a level above the upper limit of the water table, to place a horizontal slotted pipe vacuum well for vapor recovery in the gravel packing, and to fill the trench above the SVE well with soil. See Fig. 1.

In recent years in-situ bioremediation has become a potent tool for the economical remediation of groundwater contaminated with biodegradable organics (16). Aeration curtains can play a role in this technology in that they not only serve as barriers to migration of volatile organic compounds but provide oxygen for bioremediation as well. They offer a low-maintenance alternative to pump and treat systems. Other similar alternatives to pump and treat systems consist of rows of air sparging wells (17) and rows of wells containing oxygen release compounds (ORC) (18). These systems require that air and/or oxygen be dispersed between the wells, while aeration curtains provide a continuous barrier. Each type of system

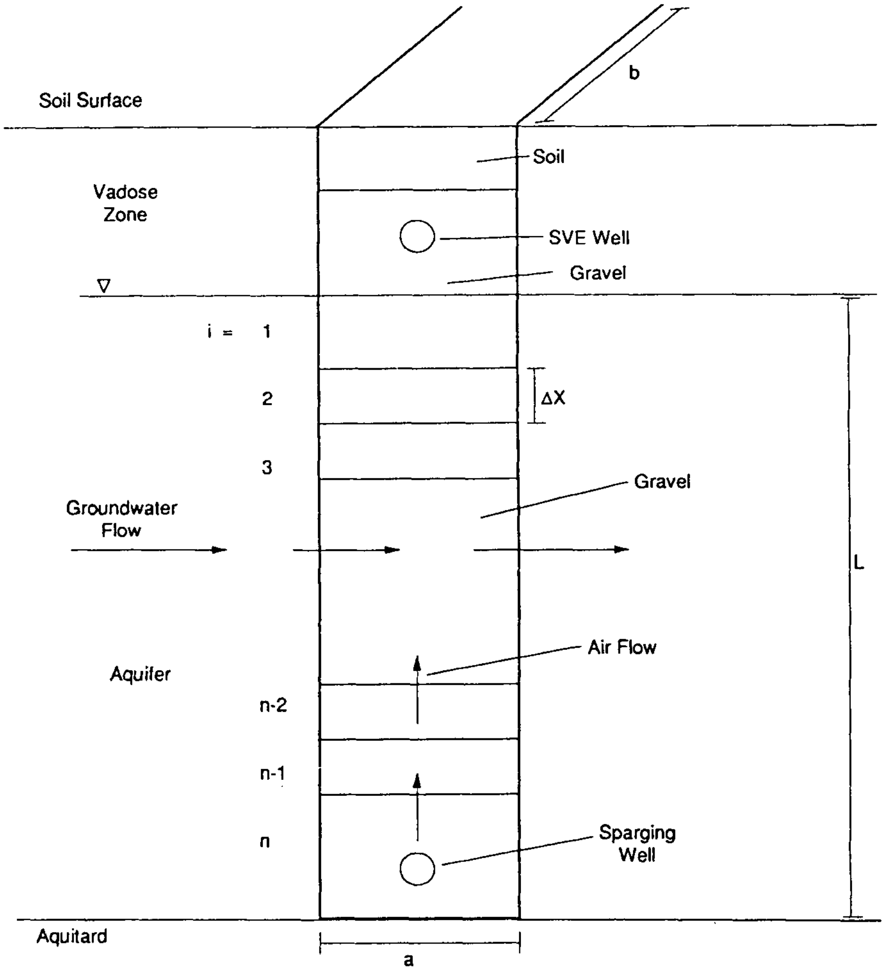


FIG. 1 Conventional crosscurrent aeration curtain design.

offers advantages over the others, depending on the site geology, available infrastructure, contaminant properties and concentrations, and location.

As we observed earlier (15), the performance of the aeration curtain design is less than one would desire unless the Henry's constants of the contaminants being removed are quite large. This difficulty can be surmounted by installing additional trenches parallel to the first, but the cost is excessive. The problem is that the crosscurrent flow design of such aeration curtains is intrinsically inefficient.

In the following sections we develop mathematical models for aeration curtains of conventional design and of two modified designs. Computations simulating the sparging of a moderately soluble volatile organic compound (VOC), trichloroethylene (TCE), are then carried out with these models under conditions selected to be generally representative of field conditions. The results of the calculations are compared and conclusions drawn. The expected impact of the modified designs on the effectiveness of these curtains in bioremediation is then examined. The paper closes with a discussion of construction feasibility and techniques.

## II. ANALYSIS

In this section we develop the sets of differential equations which constitute the models for the three cases to be examined. The models have the following features in common.

1. The contaminant is presumed to be present as dissolved VOC only.
2. The contaminant obeys Henry's law.
3. Mass transport kinetics between the aqueous phase and the gas phase is described by a single mass transport rate constant.
4. Axial dispersion is not explicitly included; choice of the number of compartments used to represent the column mathematically permits one to increase or decrease axial dispersion.
5. The permeability of the aquifer is independent of position and time.
6. The air is approximated as incompressible.



### A. Aeration Curtains of Conventional Design

We first model aeration curtains of conventional crosscurrent design. See Fig. 1 for a schematic of the configuration. Notation is as follows.

$L$ = depth of crosscurrent section of curtain, m
$a$ = cross-sectional thickness of curtain, m
$b$ = horizontal length of curtain, m
$Q_a$ = air flow rate, $m^3/s$
$V_0$ = groundwater superficial flow rate, $m^3/m^2 \cdot s$
$Q_w$ = total water flow rate through curtain, $m^3/s$
$\nu$ = porosity of curtain gravel packing
$v_b$ = bubble rise velocity, m/s
$K_H$ = Henry's constant of VOC, dimensionless
$k_f$ = mass transfer rate constant, $s^{-1}$

$n$ = number of volume elements into which the curtain is partitioned for analysis
$\Delta x$ = height of a volume element
$C_{\text{infl}}$ = VOC concentration of influent to the curtain, kg/m$^3$
$C_i^{\text{w}}$ = aqueous phase VOC concentration in the $i$th volume element, kg/m$^3$
$C_i^{\text{g}}$ = vapor phase VOC concentration in the $i$th volume element, kg/m$^3$
$C_{\text{effl}}$ = mean concentration of aeration curtain effluent, kg/m$^3$
$A$ = $ab$, horizontal cross-sectional area of curtain, m$^2$
$\Delta V$ = $\Delta xabv$, volume of one volume element, m$^3$
$\Delta V_{\text{a}}$ = air-filled volume in one volume element, m$^3$
$\Delta V_{\text{w}}$ = water-filled volume in one volume element, m$^3$

The total water flow rate to the curtain is given by

$$Q_{\text{w}} = v_0 L b \tag{1}$$

The air-filled volume in one volume element is given by

$$\Delta V_{\text{a}} = Q_{\text{a}} \Delta x / v_{\text{b}} \tag{2}$$

The water-filled volume in one volume element is given by

$$\Delta V_{\text{w}} = \Delta V - \Delta V_{\text{a}} \tag{3}$$

We assume that mass transport between the aqueous and gaseous phases is governed by

$$\left.\frac{\partial C_i^{\text{g}}}{\partial t}\right|_{\text{m.t.}} = k_{\text{f}}(K_{\text{H}} C_i^{\text{w}} - C_i^{\text{g}}) \tag{4}$$

where $k_{\text{f}}$ is the mass transport rate constant and $K_{\text{H}}$ is the Henry's constant for the VOC. Since mass transport is a conservative process within the volume element $V$, we have

$$\left.\frac{\partial C_i^{\text{w}}}{\partial t}\right|_{\text{m.t.}} = -\frac{\Delta V_{\text{a}}}{\Delta V_{\text{w}}} k_{\text{f}}(K_{\text{H}} C_i^{\text{w}} - C_i^{\text{g}}) \tag{5}$$

The flow rate of water through the $i$th volume element is given by $Q_{\text{w}}/n$. A mass balance on the aqueous phase in the $i$th volume element then gives

$$\Delta V_{\text{w}} \frac{\partial C_i^{\text{w}}}{\partial t} = \frac{Q_{\text{w}}}{n}(C_{\text{infl}} - C_i^{\text{w}}) - \Delta V_{\text{w}} \left.\frac{\partial C_i^{\text{w}}}{\partial t}\right|_{\text{m.t.}} \tag{6}$$

which in turn yields

$$\frac{\partial C_i^{\text{w}}}{\partial t} = \frac{Q_{\text{w}}}{n \Delta V_{\text{w}}}(C_{\text{infl}} - C_i^{\text{w}}) - \frac{\Delta V_{\text{a}}}{\Delta V_{\text{w}}} k_{\text{f}}(K_{\text{H}} C_i^{\text{w}} - C_i^{\text{g}}) \tag{7}$$

A mass balance on the gas phase in the $i$th volume element gives in similar fashion

$$\frac{\partial C_i^g}{\partial t} = \frac{Q_a}{\Delta V_a}(C_{i+1}^g - C_i^g) + k_f(K_H C_i^w - C_i^g) \tag{8}$$

At the bottom of the column $C^g_{n+1} = 0$, since this is the VOC concentration of the incoming air.

The effluent concentration from the curtain is calculated as the average of the effluent concentrations from the individual volume elements; it is

$$C_{effl} = (1/n) \sum_{i=1}^{n} C_i^w \tag{9}$$



### B. Aeration Curtains of Crosscurrent/Countercurrent Design

A crosscurrent/countercurrent aeration curtain is diagrammed in Fig. 2. In this design a vertical barrier is placed in the middle of the trench to force the incoming water down nearly to the bottom of the trench, where it passes under the barrier, rises on the other side of the barrier, and is discharged downgradient. We use the same notation as in the previous case.

Mass transfer between the aqueous and vapor phases is described as before, by Eqs. (4) and (5). A material balance on the aqueous phase in the $i$th volume element gives

$$\Delta V_w \frac{\partial C_i^w}{\partial t} = \frac{Q_w}{n} C_{infl} + \frac{i-1}{n} Q_w C_{i-1}^w - \frac{iQ_w}{n} C_i^w - V_a k_f(K_H C_i^w - C_i^g) \tag{10}$$

A material balance on the gas phase in the $i$th volume element gives, as before,

$$\frac{\partial C_i^g}{\partial t} = \frac{Q_a}{\Delta V_a}(C_{i+1}^g - C_i^g) + k_f(K_H C_i^w - C_i^g) \tag{8'}$$

As before, $C_{n+1}^g = 0$.

The effluent concentration from the curtain is given by

$$C_{effl} = C_n^w \tag{11}$$

since all of the water passes down under the barrier and no further air sparging takes place after the water has passed under the barrier.

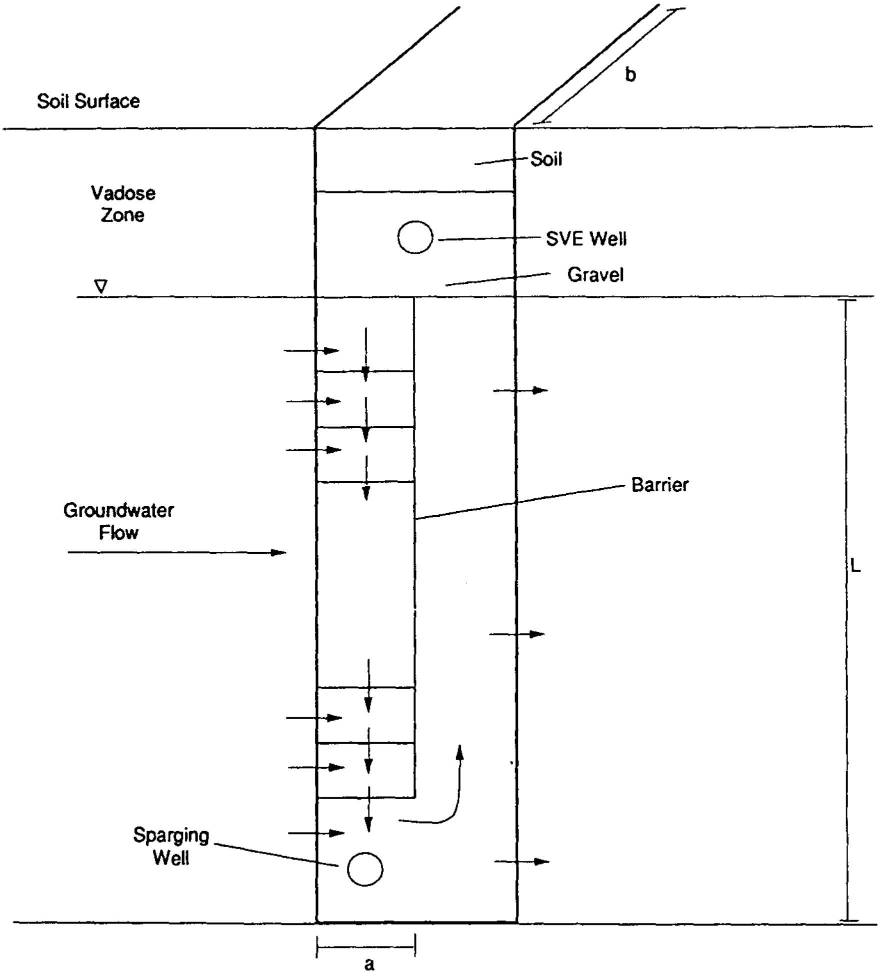


FIG. 2 Crosscurrent/countercurrent aeration curtain design.

### C. Crosscurrent/Countercurrent Aeration Curtains with a Purely Countercurrent Section at the Bottom

Here we modify the system analyzed in Section B by adding a section at the bottom of the curtain below the aquifer or contaminated zone in which no water is entering from the left, as shown in Fig. 3. This could be accomplished by constructing the aeration curtain trench down into

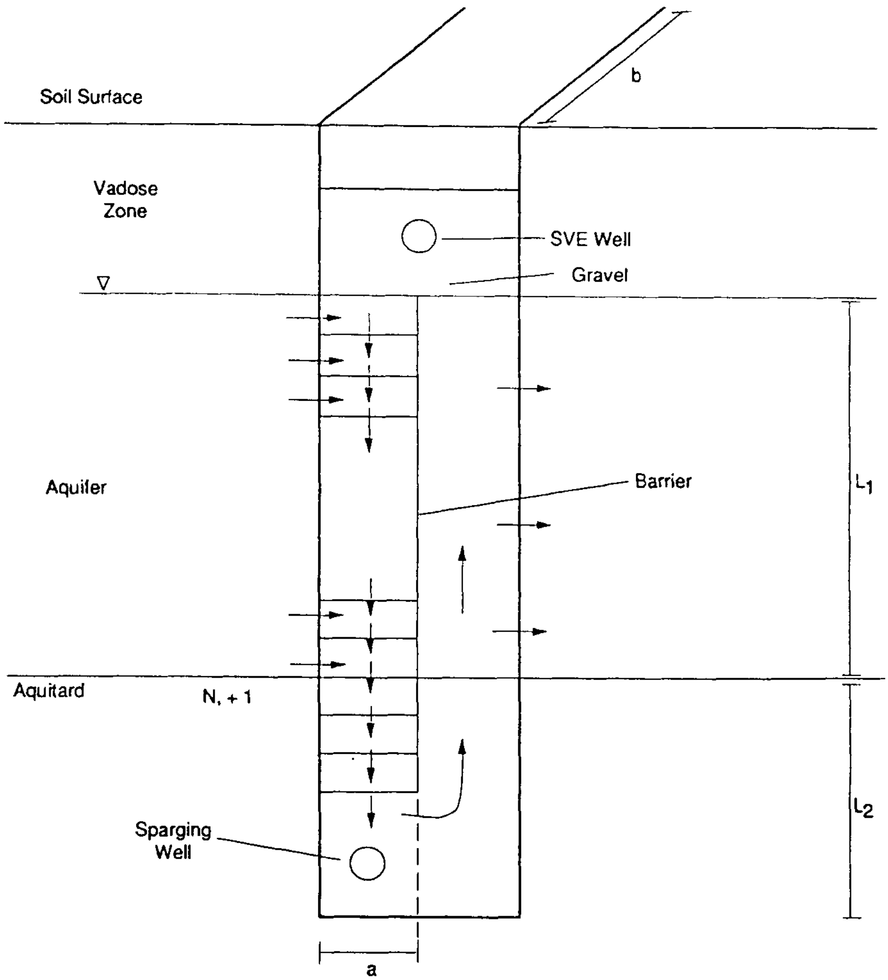


FIG. 3 Crosscurrent/countercurrent aeration curtain with countercurrent section.



an underlying aquitard or, if the contamination plume is confined to the upper portion of the aquifer, by constructing the aeration curtain through to a sufficient depth below the plume.

Some additional notation is required. Let

$n_1$ = number of volume elements in the crosscurrent/countercurrent (upper) section of the curtain

$n_2$ = number of volume elements in the countercurrent (lower) section of the curtain

The equations which describe the upper section of the curtain are virtually identical to those in Section B above; they are

$$\Delta V_w \frac{\partial C_i^w}{\partial t} = \frac{Q_w}{n_1} C_{\text{infl}} + \frac{i-1}{n_1} Q_w C_{i-1}^w - \frac{i}{n_1} Q_w C_i^w - \Delta V_a k_f (K_H C_i^w - C_i^g), \quad (12)$$

$$i = 1, 2, 3, \ldots, n_1$$

and

$$\Delta V_a \frac{\partial C_i^g}{\partial t} = Q_a(C_{i+1}^g - C_i^g) + \Delta V_a k_f (K_H C_i^w - C_i^g) \quad (8'')$$

In the lower (countercurrent) section of the curtain, Eq. (8'') governs the vapor-phase concentrations, and the aqueous-phase concentrations are controlled by

$$\Delta V_w \frac{\partial C_i^w}{\partial t} = Q_w(C_{i-1}^w - C_i^w) - \Delta V_a k_f (K_H C_i^w - C_i^g), \quad (13)$$

$$i = n_1 + 1, n_1 + 2, \ldots, n$$

where $n = n_1 + n_2$.

The VOC concentration in the water discharged from the curtain is given by

$$C_{\text{effl}} = C_n^w \quad (11')$$

as in Section B above.

Programs were written in TurboBASIC to implement these three models. A typical run to steady state on an MMG 386 machine with a math coprocessor and operating at 33 MHz required about 6 minutes. Most of the modeling was done using trichloroethylene (TCE) as the VOC, since it is a common contaminant and is less readily removed than many hydrocarbons.

## III. RESULTS

Removal of TCE was simulated for the three aeration curtain configurations; default parameters for the runs are listed in Table 1. We shall look at the dependence of curtain performance (percent TCE removed) on air flow rate for the three different types of curtains. We then examine the

TABLE 1
Default Parameters Used in the Simulations Run for the Three Aeration Configurations

| | |
|---|---|
| Depth of crosscurrent or crosscurrent/countercurrent section of curtain | 5 m |
| Horizontal length of curtain, $b$ | 10 m |
| Cross-sectional thickness of remediation section of curtain, $a$ | 0.5 m |
| Porosity of curtain packing, $\nu$ | 0.4 |
| Air flow rate, $Q_a$ | 0.010 $m^3/s$ |
| Air bubble rise velocity, $v_b$ | 5 cm/s |
| VOC mass transfer rate constant, $k_f$ | 0.1 $s^{-1}$ |
| Groundwater superficial velocity, $v_0$ | 1.0 m/day |
| Henry's constant of VOC (TCE) | 0.2821 |
| Influent VOC concentration | 100 mg/L |
| Number of compartments in crosscurrent or crosscurrent/countercurrent section | 20 |
| Number of compartments in countercurrent section (Model C only) | 6 |
| $\Delta x$ | 0.25 m |
| $\Delta t$ | 1 second |
| Duration of simulation | 0.125 days |



dependence of the performance of Model C on Henry's constant, length of the countercurrent section, and mass transfer rate. Next, we compare the performances of the three column models under identical conditions of water flow, air flow, VOC concentration, and curtain geometry. Finally, in a subsequent section, we compare their oxygen transfer performance under identical conditions.

## A. Results, Simple Crosscurrent Aeration Curtain

The TCE concentration distributions in the curtain under conditions of steady-state operation are shown in Fig. 4 for air flow rates of 0.005, 0.0075, 0.010, and 0.0125 $m^3/s$. The percent TCE removal in the water discharged from the curtain for these flow rates are given in Table 2. It is evident that this technique is removing a substantial quantity of TCE, but it is also evident that one would need several such curtains in series in order to achieve removals approaching 99%. Costs would be proportionally higher and space limitations would become a problem at many sites. Such a curtain would be effective for aeration in biosparging, facilitating degradation downgradient of the curtain, but it does not have the stripping efficiency needed for the removal of biorefractory VOCs to the target levels at most sites.

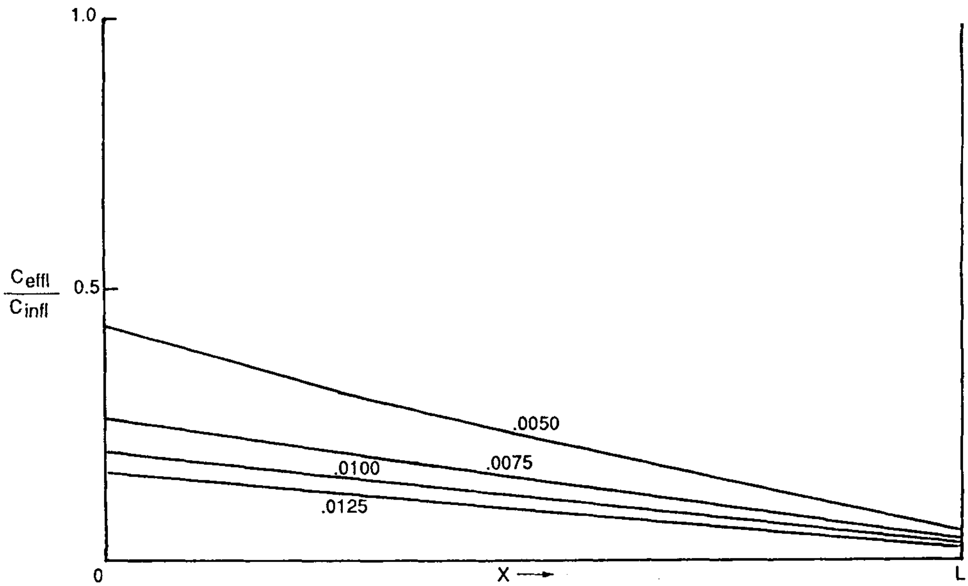


FIG. 4 Plots of aqueous concentration of contaminant in the aeration curtain versus distance from the top of the curtain, conventional crosscurrent aeration curtain. Effects of air flow rate $Q_a$. $Q_a$ = 0.0050, 0.0075, 0.0100, and 0.0125 $m^3/s$, as indicated. Other parameters as in Table 1.



## B. Results, Crosscurrent/Countercurrent Aeration Curtain

The distribution of TCE concentrations in the crosscurrent/countercurrent aeration curtain in steady-state operation are shown in Fig. 5 for air flow rates of 0.005, 0.0075, 0.0100, and 0.0125 $m^3/s$. These distributions

TABLE 2
Percent TCE Removal at Different Air Flow Rates, Simple Crosscurrent Aeration Curtain (parameters as in Table 1 except as indicated)

| Air flow rate ($m^3/s$) | Percent TCE removal |
|---|---|
| 0.0050 | 76.80 |
| 0.0075 | 84.84 |
| 0.0100 | 88.36 |
| 0.0125 | 90.52 |

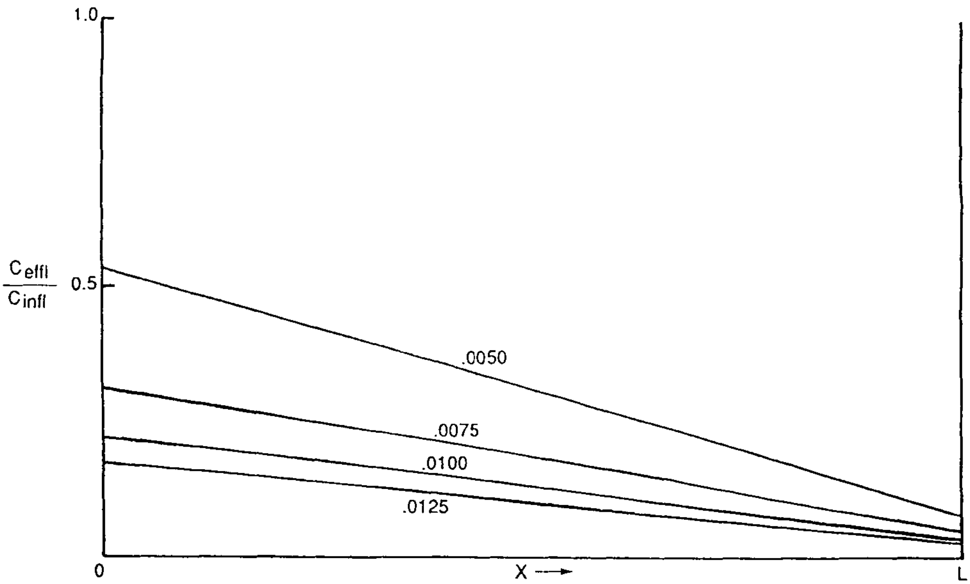


FIG. 5 Plots of aqueous concentration of contaminant in the aeration curtain versus distance from the top of the curtain, crosscurrent/countercurrent aeration curtain. Effects of air flow rate $Q_a$. $Q_a$ = 0.0050, 0.0075, 0.0100, and 0.0125 $m^3/s$, as indicated. Other parameters as in Table 1.



do not look particularly different from those for the simple crosscurrent aeration curtain. However, the curtain effluent concentration here is the concentration in the bottom volume element of the system, in contrast to the previous system where it is averaged over all volume elements.

The computed percent TCE removals for the crosscurrent/countercurrent aeration curtain are given in Table 3. Modification of the curtain by the introduction of the vertical barrier which induces the water to flow countercurrent to the air has resulted in a quite substantial improvement in performance. However, the effluent TCE concentration is still sufficiently high that target levels are unlikely to be achieved (recall that frequently 99.9% or higher removal is necessary for this). The curtain is still not attaining the very high removal efficiencies that one expects from a properly designed and operated purely countercurrent flow system.

### C. Results for a Crosscurrent/Countercurrent Aeration Curtain with a Purely Countercurrent Section at the Bottom

We have been able to devise no convenient and economical way to construct a purely countercurrent flow aeration curtain. However, the

TABLE 3
Percent TCE Removal at Different Air Flow Rates, Crosscurrent/Countercurrent Aeration Curtain (parameters as in Table 1 except as indicated)

| Air flow rate ($m^3/s$) | Percent TCE removal |
|---|---|
| 0.0050 | 91.13 |
| 0.0075 | 94.89 |
| 0.0100 | 96.38 |
| 0.0125 | 97.19 |

third model examined above provides a countercurrent flow section at the bottom and therefore might be expected to approach the high efficiencies generally found in countercurrent systems. In Fig. 6 we see the distributions of VOC concentrations in the column at steady state; this column has a purely countercurrent section at the bottom that is 1.5 m in length.



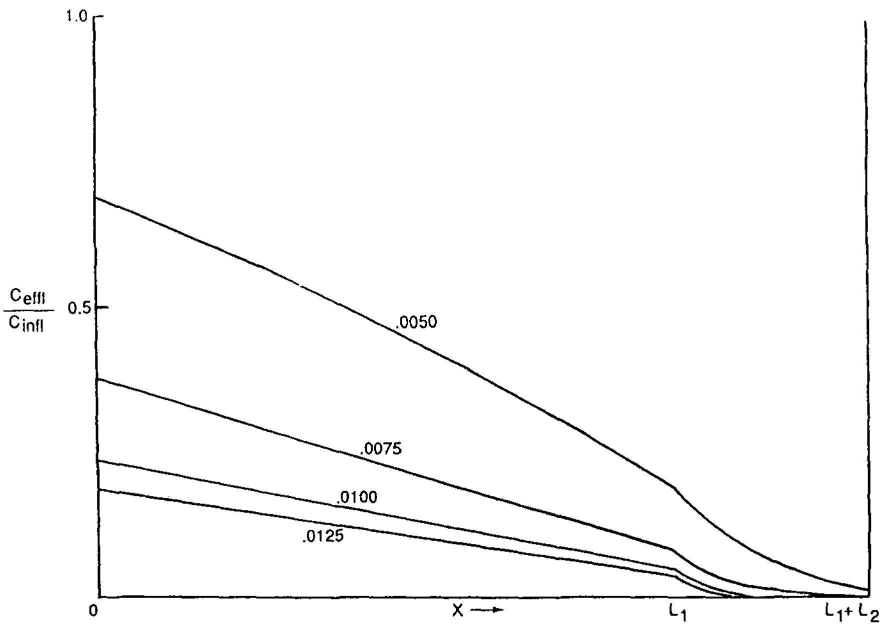


FIG. 6 Plots of aqueous concentration of contaminant in the aeration curtain versus distance from the top of the curtain, crosscurrent/countercurrent aeration curtain with a countercurrent section at the bottom of length 1.5 m. Effects of air flow rate $Q_a$. $Q_a$ = 0.0050, 0.0075, 0.0100, and 0.0125 $m^3/s$, as indicated. Other parameters as in Table 1.

TABLE 4
Percent TCE Removal at Different Air Flow Rates, Crosscurrent/Countercurrent Aeration Curtain with a Purely Countercurrent Section
(parameters as in Table 1 except as indicated)

| Air flow rate ($m^3/s$) | Percent TCE removal |
|---|---|
| 0.0050 | 98.03 |
| 0.0075 | 99.82 |
| 0.0100 | 99.97 |
| 0.0125 | 99.993 |



Air flow rates are 0.0050, 0.0075, 0.0100, and 0.0125 $m^3/s$. Note that while VOC concentration varies linearly in the crosscurrent/countercurrent section of the column, it appears to decrease exponentially in the purely countercurrent section at the bottom.

The steady-state percent TCE removals for the various air flow rates are given in Table 4. Percent removals range from 98 to over 99.99%, far higher than seen with either of the other two curtain types, and sufficiently high that one may hope to readily achieve even rather stringent target contaminant concentration requirements.

Table 5 exhibits the effect of the length of the purely countercurrent section of the curtain on percent removal. As expected, the percent removal increases with this length, but with a section length of only 1 meter almost 99.9% removal is being achieved. Evidently it is not necessary to excavate deeply in order to configure a countercurrent section of adequate

TABLE 5
Effect of Countercurrent Section Length on Percent Removal, Curtain with Countercurrent Flow Section
(parameters as in Table 1 except as indicated)

| Length of countercurrent section (m) | Percent TCE removal |
|---|---|
| 0.0 | 96.38 |
| 0.5 | 99.31 |
| 1.0 | 99.87 |
| 1.5 | 99.97 |
| 2.0 | 99.993 |

thickness, so that installation costs of such a curtain are not expected to be excessive.

The effect of the Henry's constant of the VOC on the performance of this type of aeration curtain is shown in Table 6. The length of the underlying countercurrent section is 1.5 meter. For Henry's constants of 0.05 or less, the curtain under the operating conditions of the runs is overloaded and its performance is quite poor. VOC is being supplied to the curtain at a rate faster than the chosen air flow rate (0.01 $m^3/s$) can remove it even under conditions of countercurrent flow and local equilibrium. This overload condition is not present with those runs for which for Henry's constants are 0.1 or greater, and for these Henry's constants the percent removals are 92% or greater. If mass transport is not limiting, one must have the water flow rate $Q_w < K_H$ times the air flow rate $Q_a$ to avoid overload. For this system $Q_w = 0.000579$ $m^3/s$, and the air flow rate $Q_a = 0.01$ $m^3/s$. We would therefore expect overload to be serious for $K_H$ equal to or less than 0.0579, as is in fact observed. The somewhat marginal (92.75% removal) performance observed when $K_H = 0.1$ is due to the effects of a finite mass transport rate between the aqueous and gas phases and to axial dispersion (approximated here by numerical dispersion). Evidently TCE (trichloroethylene), PCE (perchloroethylene), and BTEX (benzene, toluene, ethylbenzene, xylenes) should be readily removed.

The effect of mass transfer rate constant $k_f$ on percent TCE removal is seen in Table 7. As expected, percent removal decreases with decreasing $k_f$, but over the range considered here the effect is not large. Still, it would be advisable to design the aeration pipe and the packing to maintain as large an air–water surface in the curtain as possible—i.e., small bubbles and small bubble rise velocities. The need for small bubbles dictates that

TABLE 6
Effect of Henry's Constant on Percent VOC Removal, Curtain with Countercurrent Flow Section (parameters as in Table 1 except as indicated)

| $K_H$ (dimensionless) | Percent VOC removal |
|---|---|
| 0.025 | 39.05 |
| 0.05 | 67.17 |
| 0.1 | 92.75 |
| 0.2 | 99.76 |
| 0.2821 | 99.97 |
| 0.4 | 99.997 |

TABLE 7
Effect of Mass Transfer Rate Constant $k_f$ on Percent TCE Removal, Curtain with Countercurrent Flow Section (parameters as in Table 1 except as indicated)

| $k_f$ ($s^{-1}$) | Percent TCE removal |
|---|---|
| 0.025 | 98.24 |
| 0.05 | 99.76 |
| 0.1 | 99.97 |
| 0.2 | 99.996 |
| 0.4 | 99.9991 |



the holes in the aeration pipe be small and that the packing be such that bubbles do not consolidate and merge under horizontal surfaces or other traps, from which the air will then be released from time to time in the form of large, inefficient bubbles.

The factors affecting bubble rise velocities are presented in some detail in Perry and Chilton's handbook (20), and we have discussed the applications of these concepts to air sparging (10). Figure 10 in this reference shows that bubble diameters in the range of 0.5 to 1 mm will have rise velocities in the range of 5 to 10 cm/s.

The "bottom line" of this theoretical study is indicated in Table 8, in which the percent TCE removals achieved by the three types of curtains under identical conditions are compared. It is evident that the crosscurrent/countercurrent curtain with a lower purely countercurrent section achieves much higher cleanup levels than do the other two.

TABLE 8
Comparison of the Percent TCE Removals for the Three Types of Curtain (parameters as in Table 1)

| Type of curtain | Percent TCE removal |
|---|---|
| Crosscurrent | 88.36 |
| Crosscurrent/countercurrent | 96.38 |
| Crosscurrent/countercurrent with purely countercurrent section | 99.97 |

## IV. IMPLICATIONS FOR BIOREMEDIATION

The principal objective of an aeration curtain in bioremediation is the transfer of oxygen into the groundwater. We therefore compare the oxygen transfer performances of the simple crosscurrent aeration curtain configuration and the crosscurrent/countercurrent configurations represented by Models B and C. The parameters used are given in Table 9; the dimensionless Henry's constant used for $O_2$ is 21.1, appropriate at 0°C. Table 10 gives dimensionless Henry's constants for oxygen between 0 and 25°C. Use of the smallest reasonable Henry's constant results in transfer of the maximum amount of oxygen to reach saturation and therefore provides the most stringent test of oxygen mass transfer. The oxygen concentration of the groundwater entering the curtain was assumed to be zero.

The simple crosscurrent aeration curtain (Model A) was found to give quite good oxygen transfer. At air flow rates of 0.01, 0.001, and 0.0001 $m^3/s$, the percent saturations achieved were 99.8, 98.3, and 84.7, respectively. For the crosscurrent/countercurrent curtain (Model B) the percent saturations achieved were 99.96, 99.58, and 94.8 for these air flow rates. For the crosscurrent/countercurrent curtain with a 1-m countercurrent section at the bottom (Model C), the percent saturations achieved were 100, 99.997, and 99.35.

The performances of all three configurations are quite satisfactory. Model C, the most complex of the three configurations, also provides the most efficient oxygen transfer, but the improvement it yields over Model B and Model A would probably not justify the additional cost. Model A,



TABLE 9
Default Parameters Used for Oxygen Transfer Calculations

| | |
|---|---|
| Cross-sectional thickness of curtain | 0.5 m |
| Depth of crosscurrent or crosscurrent/countercurrent section | 5 m |
| Depth of countercurrent section (Model C) | 1 m |
| Horizontal length of curtain | 10 m |
| Porosity of curtain packing | 0.4 |
| Air flow rate | 0.01 m/s |
| Superficial groundwater velocity | 1 m/day |
| Influent oxygen concentration | 0 mg/L |
| Bubble rise velocity | 5 cm/s |
| $K_H$ for oxygen, dimensionless | 21.1 |
| Mass transfer rate constant | 0.1 $s^{-1}$ |
| $\Delta x$ | 0.25 m |
| $\Delta t$ | 1 second |

TABLE 10
Dimensionless Henry's Constants for Oxygen between 0 and 25°C[a]

| Temperature | $K_H$ |
|---|---|
| 0 | 21.1 |
| 5 | 23.8 |
| 10 | 26.5 |
| 15 | 29.1 |
| 20 | 31.6 |
| 25 | 33.9 |

[a] Calculated from data in Ref. 19.



the simple crosscurrent curtain, is slightly less efficient than the other two, but the differences are sufficiently small that one would probably not go to the extra expense of constructing a crosscurrent/countercurrent curtain if one were only interested in providing oxygen for bioremediation.

Neither of these crosscurrent/countercurrent configurations should have any detrimental effects on bioremediation as compared to the simple crosscurrent design.

We conclude that Model C is by far the most efficient curtain configuration for the air stripping of dissolved organics, having the potential of removing 99+% of such dissolved VOCs as trichloroethylene. On the other hand, if one is solely concerned with providing oxygen for bioremediation, there is nothing to be lost but little to be gained by using a more elaborate crosscurrent/countercurrent system instead of the conventional crosscurrent design.

Although the water leaving the trench will be enriched in dissolved oxygen, which will result in continued accelerated biodegradation after the water exits the trench, it may nevertheless be beneficial to increase the retention time of the biodegradable organic species within this "bioreactor." This can be done by simply adding surface area conducive to attached cell growth, as is done with fixed film reactors, so that there is more biofilm in which the organics can be absorbed. Virtually any plastic material will do. Another possible enhancement is the inclusion of slow-release nutrient products such as those made by Grace Sierra or Exxon.

## V. ASPECTS OF CONSTRUCTION

### A. Introduction

Construction of a countercurrent in-situ air stripping curtain of the sort described above as Model C could be accomplished by several techniques, depending upon subsurface conditions, depth requirements, and other factors. These techniques include:

- Specially designed trenching machines
- Polymeric, biodegradable slurry trenching
- Specially fabricated trench boxes

Other approaches also are possible, such as conventional open trench construction with or without dewatering. However, the fact that in-situ air stripping curtains must necessarily be installed to a depth below a plume in an aquifer suggests that such excavations would be highly unstable, necessitating dewatering and increasing costs to an noncompetitive level relative to the techniques listed above.

Each of these techniques is briefly described in the following paragraphs.

### B. Specially Designed Trenching Machines

Specially designed trenching machines can be employed to construct countercurrent air sparging trenches to depths of up to about 30 feet. These trenching machines are set up so as to enable simultaneous excavation of a slot trench and emplacement of perforated pipe, gravel, and interlocked geomembrane panels. Horizontal Technologies of Cape Coral, Florida, has patented such a system under the name of the POLYWALL Barrier System. HDPE (high density polyethylene) sheets in thicknesses ranging from 40 to 100 mils can be placed in lengths up to 300 feet without joints and longer with joints. Groundwater Control, Inc., of Brentwood, Tennessee, also offers a similar system.

### C. Polymeric, Biodegradable Slurry Trenching

Countercurrent air sparging trenches can also be constructed using polymeric, biodegradable slurry trenching techniques. This approach is applicable to both shallow and deep trenches. Depths up to 100 feet or more should be feasible. This technique is similar in many respects to conventional bentonite slurry trenching except that a natural or synthetic biopolymer is substituted for the bentonite clay. The biopolymer acts to increase the viscosity of the water and, in conjunction with colloids in suspension in the slurry, forms the filter cake on the trench walls which is necessary to support the trench during construction. By excavating under the biodegradable slurry, it is possible to excavate trenches to depths considerably below the groundwater table. HDPE membrane, perforated pipe, and gravel can then be placed within the trench to create the countercurrent air sparging curtain. The biopolymer then biodegrades under the attack of naturally-occurring bacteria, thus restoring the natural permeability of the soil. Natural biopolymers are derived from plant or tree gums or from algae. Synthetic biopolymers are usually produced from cellulosic esters.

## D. Specially Fabricated Trench Boxes

Another technology suitable for use in constructing countercurrent sparging curtains is a method involving specially designed trench or guide boxes. BMC Corp., of Gretna, Louisiana, markets a system under the name Enviro-Wall which uses a patented method of installation involving a series of interlocking and stackable guide box assemblies. The interlocking guide boxes measure 8 by 10 feet and are 26 inches wide. They can be stacked vertically to a depth of 30 feet. An 18-inch internal void allows for the insertion of interlocked HDPE panels, perforated pipe, and gravel. The fact that construction occurs within an open void in the interior of the guide boxes permits visual inspection of each step in the construction process—a significant advantage of competing technologies.



## E. General Considerations

Whichever construction technique is used, design of countercurrent air sparging curtains must give careful consideration to system hydraulics. The system must be capable of passing the full flow of the plume through the trench without significant hydraulic head loss which, if excessive, could result in the plume bypassing the countercurrent aeration curtain. Groundwater modeling is recommended along with careful specification and control of component permeabilities. A preliminary analysis indicates that countercurrent air sparging curtains will be most easily constructed within aquifers of low to moderate permeability. High-permeability, high-flow aquifers will be more difficult to deal with due to the proportionately larger quantities of groundwater which must be redirected. One is also more likely to have problems with trench collapse, and there is a greater potential for flow of portions of the contaminant plume around the curtain.

The perforated pipe and gravel must be designed not only to achieve sufficient hydraulic capacity but also to prevent piping. Piping refers to the movement of erodable soil into or through gravel filters or perforated pipe, often leading to clogging, loss of hydraulic capacity, and, ultimately, complete system failure. The design of these systems must find the often thin line where the pore spaces in a gravel or the perforations or slots in a pipe are large enough to permit the necessary flow of air, yet small enough to prevent piping. Cedergren (21) presents a thorough treatment of these design considerations.

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