Soil Clean-Up by Surfactant Washing. IV. Modification and Testing of Mathematical Models

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ABSTRACT

Three models for the operation of surfactant washing/flushing columns or test beds are developed. These differ in the manner in which hydrophobic contaminant is held in the soil and, therefore, in the nature of mass transfer of contaminant from the stationary phase to the advecting surfactant solution. The fitting of parameters to experimental results is addressed, following which the parameters obtained are used to simulate operation of laboratory columns and a pilot-scale test bed. The results are compared which experimental data from the column and test bed. The air stripping of biphenyl from spent surfactant solution is modeled using a local equilibrium approach to see if air stripping could account for observed losses. The air stripping of toluene from the surfactant solution is modeled using a local equilibrium approach or a lumped parameter method to model diffusion-limited kinetics.

INTRODUCTION

Soil surfactant washing is a technology which is under development for the removal of hydrophobic organic contaminants from soils when these compounds are of sufficiently low volatility that soil vapor extraction cannot be used and when the compounds are not sufficiently biodegradable to permit bioremediation techniques to be used. It competes with steam stripping and low-temperature thermal treatment. In the earlier papers in

this series, bench-scale work on soil surfactant flushing with emphases on the recycle and reuse of the surfactant and some aspects of mathematical modeling were discussed (1) and the design and evaluation of a small pilot-scale soil surfactant flushing system which included the recycle of surfactant were described and explored (2, 3). Related work on the recovery of surfactant solution for recycle has been done by Underwood et al. (4, 5).

One of the secondary objectives of the project was the modification and validation of mathematical models for the various unit operations involved in the recycle of surfactant generated during soil washing/flushing. These models could be used for evaluation and design purposes. This phase of the project builds on our earlier work (6–8). This work on mathematical models is discussed in the present paper.

Here we develop three models for the operation of surfactant washing/ flushing columns or pilot-scale test beds (2). These differ in the manner in which the hydrophobic contaminant is held in the soil and, therefore, in the nature of the process controlling the mass transfer of contaminant from the stationary phase to the advecting surfactant solution. The problem of fitting results is then addressed, following which the parameters obtained are used to simulate the operation of the columns or test bed. The results of these calculations are then compared with the experimental data obtained from the column or test bed. Also included is the modeling of the flushing of toluene from the soil test bed.

In the course of the pilot-scale runs reported earlier (3), it was found that substantial quantities of semivolatile biphenyl were apparently being removed during the air stripping of the spent (contaminated) surfactant solution. This step is included in the surfactant recycle process to remove volatile components early in the scheme to permit a simpler recovery of the extracting solvent later in the process. Therefore, the removal of biphenyl from the spent surfactant solution by an air-stripping column was modeled using a local equilibrium approach to see if air stripping could account for the observed losses. The air stripping of toluene from the surfactant solution was also modeled. The two models employed for the air stripping of toluene used either a local equilibrium approach or a lumped parameter method to model diffusion-limited kinetics.

MODELS FOR SURFACTANT FLUSHING/WASHING

Mathematical Analysis of a Soil Column or Test Bed

A schematic of the soil column or test bed to be modeled is given in Fig. 1. All three of the surfactant flushing models have in common the following notation.

h = height of soil column/test bed, cm
r_c = radius of column or test bed, cm
n = number of volume elements into which the column is partitioned for
    mathematical analysis
Δx = h/n, thickness of a volume element, cm
A = πr_c^2, cross-sectional area of column, cm^2
ΔV = $A \Delta x$, volume of one volume element, cm^3
Q = flow rate of surfactant solution through the column, cm^3/s
v = porosity of medium
ρ_s = density of soil, g/cm^3
ρ_c = density of contaminant, g/cm^3
C_i = concentration of immobile contaminant, g/cm^3 of bulk soil
c_i = concentration of solubilized contaminant, g/cm^3 of aqueous phase
m_i = $\Delta V(v c_i + C_i)$, mass of contaminant in ith volume element, g

Model 1. Linear Adsorption Isotherm

For our first model, it is assumed that the relationship between c_i and C_i at equilibrium is a linear one, so that

$$c_i^e = KC_i \tag{1}$$

where K is the isotherm constant and c_i^e is the aqueous phase (surfactant solution) contaminant concentration in equilibrium with an immobile soil contaminant concentration of C_i. The above definition of m_i and a mass balance on the ith volume element then yield

$$\frac{dm_i}{dt} = v\Delta V\frac{dc_i}{dt} + \Delta V\frac{dC_i}{dt} = Q(c_{i-1} - c_i) \tag{2}$$

The mass transport kinetics of contaminant movement from the stationary phase to the advecting solution is then modeled by means of a lumped parameter approach. We postulate Eq. (3) for this.

$$\frac{dC_i}{dt} = -\lambda(c_i^e - c_i) = -\lambda(KC_i - c_i) \tag{3}$$

Here λ is the rate constant (s^{-1}) for the desorption–solution processes. Solution of Eq. (2) for dc_i/dt and use of Eq. (3) then yields

$$\frac{dc_i}{dt} = \frac{Q}{v\Delta V}(c_{i-1} - c_i) + \frac{\lambda}{v}(KC_i - c_i), \qquad i = 1, 2, 3, \ldots, n \tag{4}$$

where we define c_0 as the contaminant concentration in the influent surfactant solution (c_0 = zero if fresh surfactant is being used).

FIG. 1   Surfactant flushing soil column/test bed model and notation.

The model parameters are then entered, the initial values of the C_i are assigned, and modeling is then carried out by integrating the set of Eqs. (3) and (4) forward in time. The contaminant concentration in the effluent at any time during the run is given by c_n, and the total mass of residual contaminant is given by

$$m_{tot} = \sum_{i=1}^{n} m_i = \Delta V \sum_{i=1}^{n} (vc_i + C_i) \tag{5}$$

Model 2. NAPL Droplet Model

In the second model it is assumed that the immobile contaminant is present in the form of trapped NAPL droplets which are surrounded by a stationary aqueous phase with a boundary layer large in thickness compared to the radius of the droplets. Contaminant must dissolve in the quiescent aqueous phase and diffuse to the mobile liquid in order to be removed. This model for solution kinetics has been examined in connection with the modeling of pump-and-treat operations (9) and sparging (10). In Ref. 9 it is shown that dC_i/dt is given by

$$\frac{dC_i}{dt} = \frac{-3C_0^{2/3}D(c_s - c_i)C_i^{1/3}}{\rho_c \alpha_0^2} \tag{6}$$

where α_0 = initial radius of NAPL droplets, cm
  C_0 = initial soil contaminant concentration, g/cm^3
  c_s = saturation concentration of contaminant in the surfactant solution being used, g/cm^3
  D = diffusivity of the contaminant in the aqueous phase in the porous medium, cm^2/s

By the procedure used in the previous model, we obtain

$$\frac{dc_i}{dt} = \frac{Q}{v\,\Delta V}(c_{i-1} - c_i) - (1/v)\frac{dC_i}{dt} \tag{7}$$

Equations (6) and (7) constitute the model. As before, one assigns values to the model parameters and an initial value C_0 to the C_i, and then integrates the equations forward in time to model a run.

Model 3. NAPL Dispersed in Porous Low-Permeability Spheres

In the third model it is assumed that the contaminant is trapped as very small NAPL droplets in porous spherical domains of low permeability and radius b. The domains are assumed to have initially a uniform distribution of NAPL throughout; as advecting surfactant solution moves past these domains, the NAPL in the outer layers of the domains gradually dissolves and diffuses to the surfaces of the domains, where it is swept away by the moving aqueous surfactant. This model was developed for use in models for groundwater pump-and-treat operations where diffusion transport is a problem. In Ref. 9 it shown that the equation governing the C_i is

$$\frac{dC_i}{dt} = \frac{3fD(c_s - c_i)(C_i/C_0)^{1/3}}{b^2[1 - (C_i/C_0)^{1/3}]} \tag{8}$$

where f = fraction of aquifer medium which consists of the low-perme-
ability porous domains

b = radius of low-permeability porous domains, cm

The equation for the dc_i/dt in Model 3 is Eq. (7), used above in Model 2. Note that initially one has zero denominators in Eq. (8); this difficulty was circumvented by multiplying the term $(C_i/C_0)^{1/3}$ in the denominator by a number slightly less than 1 (typically 0.9 or 0.94).

Results of Soil Column/Test Bed Models

The numerical integration of the differential equations in all the models was carried out by a standard predictor-corrector method. Microcomputers equipped with 80286 or 80386 processors and with math coprocessors and running under MS-DOS at clock speeds of 12 to 33 MHz were used. A typical run required just a few minutes.

Axial dispersion in all three models is handled by the choice of the number n of volume elements into which the column is partitioned; the larger the n, the smaller the axial dispersion. Results were relatively insensitive to this parameter; lower values of n tended to give somewhat more tailing in plots of residual contaminant mass (m_{tot}) versus number of pore volumes of surfactant passed through the column (V_p). In preliminary work, it was found that choices of parameters could be made in the models such that plots of m_{tot} versus V_p were virtually indistinguishable. Model 2 was therefore arbitrarily selected for use with the experimental data.

In fitting this model to experimental results, one sees that it is not possible to obtain unique values for D and α_0, since these appear only in the combination D/α_0^2. We therefore elected to assign what we felt to be a reasonable value to D, 2×10^{-6} cm/s, and make all data-fitting adjustments by varying α_0. The quantity α_0^2/D has the units of seconds, and can be regarded as a time constant for the diffusion process. For example, if $\alpha_0 = 0.1$ cm, this time constant has a value of 5000 seconds, or slightly over 80 minutes.

Experiments were first performed using stirred batch systems in which soil spiked with biphenyl was placed in Erlenmeyer flasks and 2% by weight sodium dodecyl sulfate (SDS) solution was added. An SDS solution was used in all experiments as the surfactant solution. The flasks were then agitated on a shaker for various periods of time, the sediment allowed to settle, and samples of supernatant taken for analysis. These experiments did not yield data on a time scale sufficiently short to permit study of the kinetics of solution; they merely established that the time constants

for these systems were substantially shorter than 24 hours. We, therefore, turn to the interpretation of the column flushing data for an estimate of the time constant for solution/diffusion.

As mentioned earlier (3), some of the soil column runs were plagued by low flow rates which drastically decreased during the course of the run, and in all runs the surfactant flow rate varied during the course of the run. Three runs in which at least six pore volumes of effluent were obtained at reasonable flow rates were selected for interpretation with Model 2. The parameter values used in making the plots shown in Figs. 2, 3, and 4 are given in Table 1. In these plots the mass of residual biphenyl in the column, m_{tot}, is plotted as a function of the number of pore volumes of surfactant solution passed through the column, V_p. The circles in the figures correspond to the experimental values obtained for the three runs.

For most of the course of the runs, it is possible to get a reasonably good fit between the theoretical curves and the experimental data points. In runs 1 and 2, however, the experimental results exhibit some tailing along toward the end of the run which could not be duplicated by Model 2. This is thought to be due to the presence in the soil of a relatively small fraction of the biphenyl in a more strongly adsorbed form.

TABLE 1

Model 2 Parameters Used in Surfactant Flushing Column Simulation[a]

	Run no. (column no.)		
Parameter	1 (16)	2 (17)	3 (20)
Column diameter, cm	6.35	6.35	6.35
Soil column length, cm	40.6	40.6	40.6
n, number of volume elements	3	3	3
Mean surfactant solution flow rate, cm³/min	0.25	0.232	0.0916
Soil porosity	0.233	0.242	0.249
Soil density, g/cm³	1.04	1.04	0.995
Solubility of biphenyl in 2.5% SDS, mg/L	1,500	1,500	1,500
Diffusion constant D, cm²/s	2×10^{-6}	2×10^{-6}	2×10^{-6}
Initial contaminant concentration, mg/kg	1000	1000	1000
Density of neat contaminant, g/cm³	1.041	1.041	1.041
Initial diameter of NAPL droplets, cm	0.02, 0.05, 0.08	0.02, 0.05, 0.08	0.02, 0.05, 0.08, 0.15

[a] For removal of biphenyl by a 2.5% SDS solution.

MEGEHEE ET AL.

FIG. 2 Comparison of Model 2 results (curves) with experimental column data, Run #1, parameters as in Table 1, droplet diameters = 0.02, 0.05, and 0.08 cm.

NUMBER OF PORE VOLUMES ELUTED

FIG. 3   Comparison of Model 2 results (curves) with experimental column data, Run #2, parameters as in Table 1, droplet diameters = 0.02, 0.05, and 0.08 cm.

MEGEHEE ET AL.
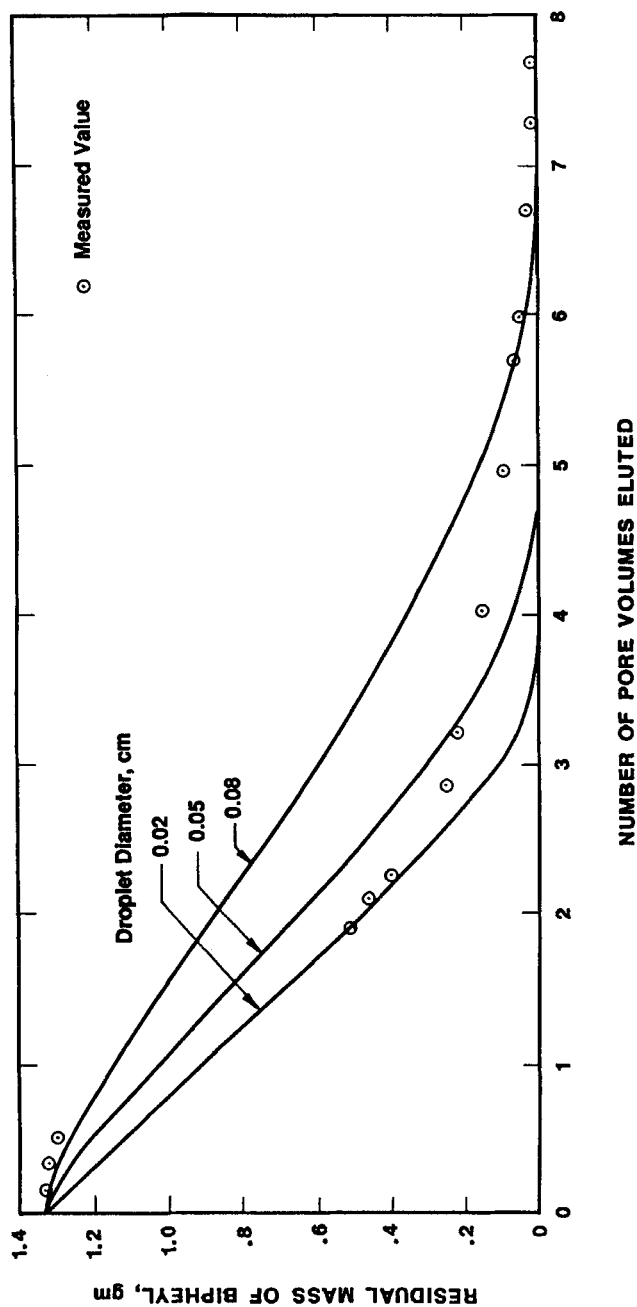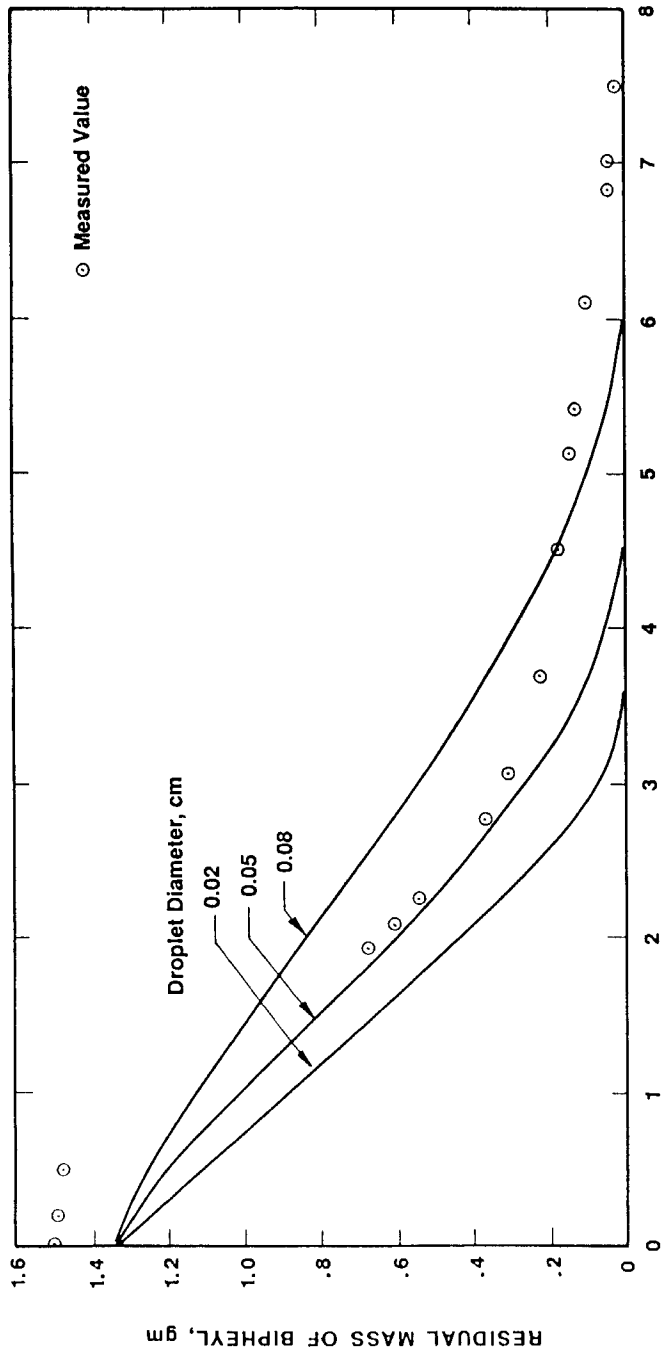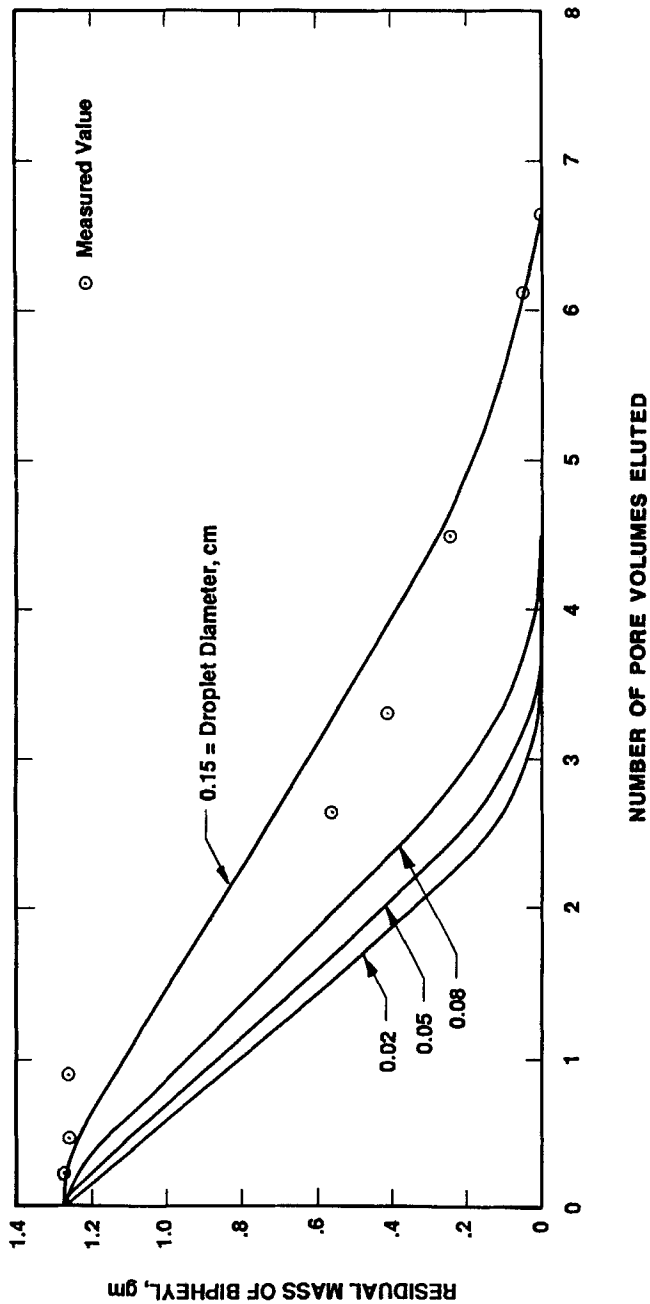

FIG. 4   Comparison of Model 2 results (curves) with experimental column data, Run #3, parameters as in Table 1, droplet diameters = 0.02, 0.05, 0.08, and 0.15 cm.

TABLE 2
Model 2 Parameters Used in Soil Test Bed Simulation[a]

Column diameter, cm	42.9
Soil column length, cm	30.9
n, number of volume elements	3
Mean surfactant solution flow rate, cm^3/min	21.76
Soil porosity	0.5118
Soil density, g/cm^3	1.14
Solubility of biphenyl in 2.5% SDS, mg/L	1500
Diffusivity of biphenyl in the porous medium, cm^2/s	2×10^{-6}
Initial contaminant concentration, mg/kg	100
Density of biphenyl, g/cm^3	1.041
Initial diameter of NAPL droplets, cm	0.05, 0.08, 0.15

[a] For removal of biphenyl by a 2.5% SDS solution.

The parameters used to model the pilot-scale test bed data are given in Table 2. The solubility of biphenyl in 2.5% aqueous SDS and the initial droplet size assumed are within the limits indicated by the column results. Some uncertainty is bound to occur due to variations in the ways in which the columns and the test bed were packed, but this does not appear to be large. The results of the Model 2 computer run are compared with the experimental data in Fig. 5. Again, some tailing in the experimental results is observed along toward the end of the run. Still, the theoretical results (obtained with parameters selected on the basis of the column data) are in reasonably good agreement with the experimental data from the test bed (3). The model thus appears to have passed this first preliminary test.

TABLE 3
Model Parameters Used for Simulating the Surfactant Flushing of Toluene in a
Laboratory Column

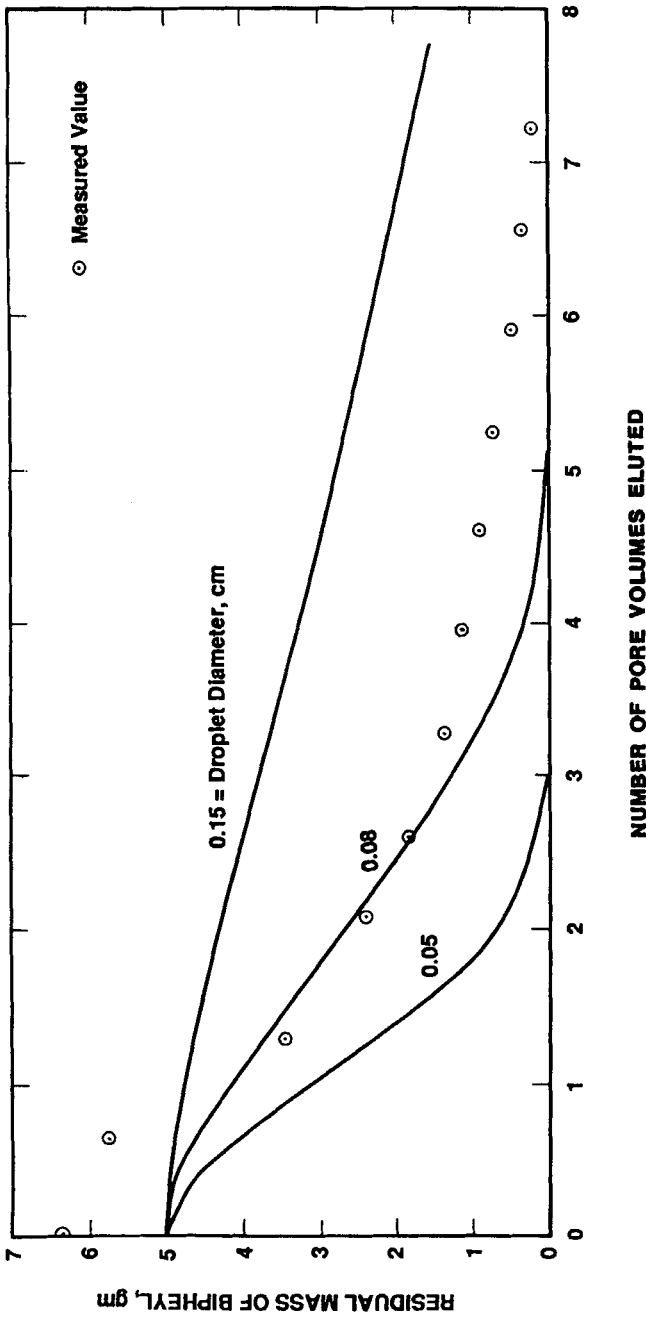|	
Column diameter, cm	6.35
Column length, cm	17.1
Number of compartments used to represent the column	5
Surfactant solution flow rate, mL/min	1.31
Soil porosity	0.203
Soil density, g/cm^3	0.994
Solubility of toluene in 2.5% SDS, mg/L	15,000
Toluene diffusivity, cm^2/s	2×10^{-6}
Initial toluene concentration in the soil, mg/kg	5,600
Density of toluene, g/cm^3	0.867
Initial diameter of toluene droplets, α_0, cm	0.04, 0.05, 0.06
dt, seconds	10

FIG. 5   Comparison of Model 2 results (curves) with experimental soil test bed data, Run #1, parameters as in Table 2, droplet diameters 0.05, 0.08, and 0.015 cm.
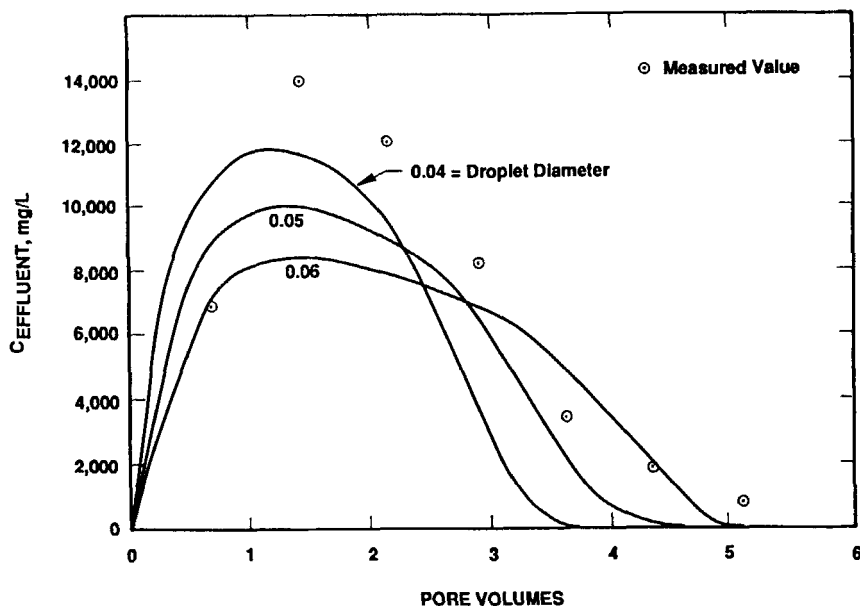
FIG. 6   Toluene removal curves, calculated from surfactant flushing column model; see Table 3 for input parameters.

Several runs were made with surfactant flushing column Model 2 for comparison with data from a run on the surfactant flushing of toluene from soil in a laboratory test column. The model parameters used are given in Table 3. The experimental points (circles) and the calculated results are shown in Fig. 6. Agreement between the two appear to be reasonably good, although the experimental results suggest that the initial concentration of toluene in the soil may have been somewhat higher than the value of 5600 mg/kg used in the model, which was based on the reported amount of toluene initially mixed into the test soil.

MODELING OF THE AIR STRIPPING OF CONTAMINANTS FROM SURFACTANT SOLUTION

Biphenyl

In the course of operating the pilot-scale air-stripping column, it was found that substantial quantities of biphenyl apparently were removed along with the much more volatile toluene. On the order of 50% of the biphenyl was typically removed (3). The relatively low volatility of biphenyl made this result seem somewhat surprising. It was, therefore, de-

cided to simulate the process to see if these results were reasonable or if they indicated some flaw in the methodology, chemical analyses, etc. A model for the operation of a countercurrent air stripping column was developed which assumed local equilibrium between the liquid and vapor phases with respect to VOC transport and that this equilibrium obeys Henry's law. The analysis proceeds as follows.

The column is partitioned into n compartments, with the aqueous phase and air flowing into the column at the top and bottom, respectively. Terms are defined as follows:

h = column height, cm
r = column radius, cm
Q_a = volumetric air flow rate, cm^3/s
Q_w = volumetric water flow rate, cm^3/s
n = number of compartments into which the column is partitioned
c_i^w = VOC concentration in the aqueous phase in compartment i, g/cm^3
c_i^a = VOC concentration in the vapor phase in compartment i, g/cm^3
m_i = mass of VOC in the ith compartment, g
$\Delta V = \pi r^2 \Delta x$ = volume of a compartment, cm^3
f_w = fraction of column volume occupied by water
f_a = fraction of column volume occupied by air
$\Delta V_a = f_a \Delta V$, air volume in compartment, cm^3
$\Delta V_w = f_w \Delta V$, water volume in one compartment, cm^3
K_H = Henry's law constant of the VOC in the surfactant solution, dimensionless

From Henry's law and the assumption of local equilibrium we have

$$c_i^a = K_H c_i^w \qquad (9)$$

Also,

$$m_i = \Delta V_w c_i^w + \Delta V_a c_i^a \qquad (10)$$

From Eqs. (9) and (10), we obtain

$$c_i^w = \frac{m_i}{\Delta V_w + K_H \Delta V_a} \qquad (11)$$

and

$$c_i^a = \frac{K_H m_i}{\Delta V_w + K_H \Delta V_a} \qquad (12)$$

A mass balance on total VOC in the ith compartment then yields

$$\frac{dm_i}{dt} = Q_w(c_{i-1}^w - c_i^w) + Q_a(c_{i-1}^a - c_i^a) \tag{13}$$

As boundary conditions, we have

$$c_0^w = C_0 \tag{14}$$

and

$$c_{n+1}^a = 0 \tag{15}$$

The column is assumed to contain no VOC initially. The model parameters are read in, and the m_i initialized to 0. The set of Eqs. (13) is then integrated forward in time, with the c_i^w and c_i^a calculated at each time step by Eqs. (11) and (12), respectively. The computer program is then run until a steady state is achieved. The aqueous effluent VOC concentration is c_n^w. The effluent concentrations so calculated are lower bounds, since the mass transport of VOC between phases is assumed to be at local equilibrium.

The Henry's constant for a VOC dissolved in a surfactant solution was calculated as follows: The vapor pressure of the VOC (biphenyl) was taken as

$$\log_e P(T) = 19.03 - 6537/T \tag{16}$$

where $P(T)$ = VOC vapor pressure at temperature T, torr
T = column operating temperature, °K

The constants in Eq. (16) were computed by a least-squares fit of vapor pressure data reported in the *CRC Handbook of Chemistry and Physics*. The vapor pressure of biphenyl at 29°C was calculated to be 0.074 torr.

The solubility of biphenyl in the 2.5% SDS solution used was taken at c_{sat} = 1500 mg/L, the value used to fit the surfactant flushing column data and the surfactant flushing test bed data. Henry's constant is then given by

$$K_H = \frac{(MW) \cdot P(T)}{0.760 \cdot 0.08206 \cdot T \cdot c_{sat}} \tag{17}$$

where (MW) = VOC molecular weight, g/mol [154.2 for biphenyl]
c_{sat} = saturation concentration of VOC in surfactant solution, mg/L

The parameters used in the model are given in Table 4. The parameter n, the number of theoretical transfer units, gives a measure of the axial

TABLE 4
Parameters Used in Simulating the Air Stripping of Biphenyl from Aqueous SDS Solution

Column height, cm	183
Column diameter, cm	15.2
Air flow rate, L/s	2.5
Water flow rate, L/s	0.0085
Air-filled fraction of the column	0.7
Water-filled fraction of the column	0.1
Molecular weight of biphenyl, g/mol	154
Influent biphenyl concentration, mg/L	100
Temperature, °C	29
Vapor pressure of biphenyl, torr	0.074
Saturation concentration of biphenyl in 2.5% SDS solution, mg/L	1500
n, number of theoretical transfer plates	3, 5, 7, 9

dispersion in the column; the larger the value of n, the smaller the axial dispersion.

The results of four simulations are given in Table 5. It is evident that the model readily yields percent removals comparable to those observed experimentally. Since this local equilibrium model does not include mass transfer kinetics limitations, we expect to get an upper bound to the removal efficiency. Had the model yielded removal efficiencies substantially less than those observed, this would have raised serious doubt about the experimental data. In fact, the model results indicate that biphenyl removal efficiencies of the order of 50% in the air-stripping column are to be expected.

Toluene

Attempts to interpret the results of the Phase I pilot-scale air stripping of toluene (2) in terms of the local equilibrium stripping column model

TABLE 5
Column Effluent Biphenyl Concentrations from the Model Runs

n^a	Effluent biphenyl concentration after one pass through the column (mg/L)	Removal efficiency after four passes (%)
2	88.29	39.2
3	88.16	39.6
5	88.14	39.6
7	88.14	39.6

[a] Where n is the number of theoretical transfer plates.

described were unsuccessful; the local equilibrium model consistently pre-dicted excessively high toluene removals for reasonable values of the model parameters. The experimental results were such as to indicate that toluene removal in these runs was diffusion-limited. A model which in-cludes diffusion kinetics by means of a lumped parameter approach was therefore developed and used to interpret the data from these experiments. We use the same notation as in the last section, with the addition of the following terms.

c_i^{we} = equilibrium aqueous VOC concentration in ith volume element, g/cm^3

c_i^{ae} = equilibrium vapor VOC concentration in ith volume element, g/cm^3

λ = rate constant for diffusion-controlled mass transport, s^{-1}

Diffusion is modeled by assuming that its rate is proportional to the difference between the actual aqueous VOC concentration and the equilib-rium VOC concentration in each compartment; this yields

$$\left(\frac{\partial c_i^w}{\partial t}\right)_{\text{diff}} = -\lambda(c_i^w - c_i^{we}) \tag{18}$$

Here c_i^{we} is given by

$$c_i^{we} = \frac{\Delta V_w c_i^w + \Delta V_a c_i^a}{\Delta V_w + K_H \Delta V_a} \tag{19}$$

If one carries out mass balances on the VOC in the aqueous and vapor phases in the ith volume element, including aqueous and vapor advective transport from adjacent volume elements and diffusion transport between the aqueous and vapor phases in the ith volume element, one readily obtains the following system of equations:

$$\frac{dc_i^w}{dt} = \lambda(c_i^{we} - c_i^w) + \frac{Q_w}{\Delta V_w} (c_{i-1}^w - c_i^w) \tag{20}$$

and

$$\frac{dc_i^a}{dt} = -\frac{\Delta V_w \lambda}{\Delta V_a} (c_i^{we} - c_i^w) + \frac{Q_a}{\Delta V_a} (c_{i+1}^a - c_i^a) \tag{21}$$

Boundary conditions are

$$c_{n+1}^a = 0 \tag{22}$$

$$c_0^w = c_{\text{influent}} \tag{23}$$

TABLE 6

Model Parameters Used in Toluene Stripping Performed during Phase 1 Testing

Height of column, cm	183
Diameter of column, cm	15.2
Number of volume elements used	5
Air flow rate	(as reported in Table 8)
SDS solution flow rate	(as reported in Table 8)
SDS solution-filled fraction of column	0.1
Air-filled fraction of column	0.7
Influent VOC concentration	(as reported in Table 8)
Molecular weight of VOC, gm/mol	92.1
Temperature, °C	16
Vapor pressure of VOC, torr[a]	16.9
Solubility of VOC in 2.5% SDS, mg/L	15,000
Time constant for diffusion mass transport $(1/\lambda)$, seconds	13

[a] Value calculated from $\log_{10} P(T) = 8.2910 - 2041.3/T$, obtained by a least squares fit to toluene vapor pressure data taken from the *CRC Handbook of Chemistry and Physics*.

To model column operation, Eqs. (20) and (21) are integrated forward in time, and the c_i^{ye} are calculated at each step forward in time by means of Eq. (19).

The parameters used, the effluent toluene concentrations, and the percent removals are given in Tables 6, 7, and 8. The results of the calculations are certainly consistent with diffusion control of the stripping column process as it was operated for these runs. The variation in Phase I operating conditions (2) is not sufficient to make this comparison a good verification of the model, however.

Model runs were also made to simulate the removal of toluene from the surfactant solution in the air stripping column using the improved

TABLE 7

Results of Modeling the Air Stripping of Toluene during Phase I Testing

Test number[a]	Experimental effluent concentration (mg/L)	Experimental percent removal	Modeled effluent concentration (mg/L)	Modeled percent removal
1	900	63	830	51
2	290	87	292	86
3	280	83	296	82
4	250	77	197	82
5	3	88	3.5	87

[a] See Table 8 for operating conditions.

TABLE 8
Air-Stripping Column Test Results—Phase I

	Virgin SDS solution spiked with toluene			SDS solution from soil bed containing toluene	
	Test 1	Test 2	Test 3	Test 4	Test 5
Air flow (L/min)	100	200	250	250	200
SDS solution flow (mL/min)	500	200	250	250	200
Toluene data:					
Concentration in (ppm)	2400	2160	1630	1080	26
Concentration out (ppm)	900	290	280	250	3
Percent removal	63	87	83	77	88

Phase II operating conditions (i.e., increased air flow, saturated air, elevated temperatures) (3). The lumped parameter model used to interpret the early air-stripping column results for toluene was used here; the parameters are given in Table 9 and are the same (except for air flow and water flow rates, temperature, vapor pressure, and influent VOC concentration) as were used for interpreting the earlier toluene results. The results of the modeling are given in Table 10. It is apparent that, under the operating

TABLE 9
Parameters Used in Simulating the Air Stripping of Toluene from Aqueous SDS Solution Using Phase II Operating Conditions

Column height, cm	183
Column diameter, cm	15.2
Air flow rate, L/s	2.5
Water flow rate, L/s	0.0085
Air-filled fraction of the column	0.7
Water-filled fraction of the column	0.1
Molecular weight of toluene, g/mol	92.1
Influent toluene concentration, mg/L	100
Temperature, °C	29
Vapor pressure of toluene, torr[a]	34
Saturation concentration of toluene in 2.5% SDS solution, mg/L	15,000
$1/\lambda$, seconds	13
n, number of theoretical transfer plates	2, 3, 5, 7, 9, 11

[a] Toluene vapor pressure calculated from $\log_{10} P(T) = 8.2910 - 2041.3/T$ obtained from a least-squares fit to toluene vapor pressure data taken from the *CRC Handbook of Chemistry and Physics*.

TABLE 10
Air-Stripping Column Effluent Toluene Concentrations from the Model Runs Using
Phase II Operation Conditions[a]

n^b	Effluent toluene concentration after one pass through the air stripping column (mg/L)	Removal efficiency after four passes through the air stripping column (%)
2	32.46	98.89
3	27.82	99.40
5	23.67	99.69
7	21.76	99.78
9	20.66	99.82
11	19.95	99.84

[a] See Table 9.
[b] Where n is the number of theoretical transfer plates.

conditions used for the column, one would expect to remove on the order of 99% or better of the toluene present in the soil test bed effluent surfactant solution in four passes through the air-stripping column.

CONCLUSIONS

The modeling of column and test bed surfactant flushing experiments appears to yield good agreement with the data, except that the experimental results show some tailing along at the ends of the runs. This is presumably due to the binding of a portion of the organic contaminant on strongly adsorbing sites. Somewhat surprisingly, the semivolatile organic biphenyl is removed from surfactant solutions to a substantial extent in the course of air stripping toluene from them; this is in agreement with model predictions, however. Mass transport kinetics appears to be a limiting factor in the air stripping of toluene from surfactant solutions.

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