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

Soil Clean Up by *in-situ* Aeration. XIV. Effects of Random Permeability Variations on Soil Vapor Extraction Clean-Up Times

James J. Bolick JR.[a]; David J. Wilson[a]
[a] DEPARTMENT OF CHEMISTRY, BOX 1822, STATION B, VANDERBIL T UNIVERSITY NASHVILLE, TENNESSEE

To cite this Article Bolick JR., James J. and Wilson, David J.(1994) 'Soil Clean Up by *in-situ* Aeration. XIV. Effects of Random Permeability Variations on Soil Vapor Extraction Clean-Up Times', Separation Science and Technology, 29: 6, 701 — 725

To link to this Article: DOI: 10.1080/01496399408005604

URL: http://dx.doi.org/10.1080/01496399408005604

SEPARATION SCIENCE AND TECHNOLOGY, 29(6), pp. 701–725, 1994

Soil Clean Up by *in-situ* Aeration. XIV. Effects of Random Permeability Variations on Soil Vapor Extraction Clean-Up Times

JAMES J. BOLICK JR. and DAVID J. WILSON*
DEPARTMENT OF CHEMISTRY
BOX 1822, STATION B
VANDERBILT UNIVERSITY
NASHVILLE, TENNESSEE 37235

ABSTRACT

A local equilibrium linear isotherm model for soil vapor extraction by means of a horizontal slotted pipe was used to explore the effects of random variations in permeability and concentration distribution and of the extent to which the contaminant volatile organic compound (VOC) has spread. The results indicate that variations in the permeability (represented by a Fourier series with random phases) can produce large variations in 99.9% clean-up times. Spatial fluctuations in the initial VOC concentration, on the other hand, produce only minor variations in clean-up times. The extent to which the contaminant VOC has spread in the domain of influence of the well has a very profound effect on the clean-up time required, indicating that very substantial savings in clean-up costs can result from rapid response after a spill has occurred.

INTRODUCTION

Soil vapor extraction (SVE, soil venting, soil vapor stripping, soil vacuum extraction) is presently the most widely used innovative technology at National Priority List sites, with 62 projects in predesign/design, 18 projects being installed or operational, and 3 projects completed. During the past 4 years the use of SVE has increased more than any other tech-

* Address for August 1993–July 1994: Departamento de Ingeniería Química, Facultad de Ciencias, Universidad de Málaga, Campus Universitario de Teatinos, 29071 Málaga, Spain.

nique due to its low cost and its effectiveness against a very common contaminant, volatile organic compounds (VOCs). When used to enhance biodegradation (bioventing), it not only permits removal of VOCs but degradation of semivolatiles. See Ref. 1. EPA has provided an excellent introduction to the technique in their reference handbook (2).

One problem with the SVE technique has been its tendency to exhibit substantial tailing and long-drawn-out clean ups at some types of sites. Feenstra and Hennet (3) remarked that this has been a serious drawback at some sites, and the report cited above (1) notes that SVE is "not effective in removing contaminants that are entrapped within the soil matrix." DiGiulio et al. (4) discussed possible pilot scale experiments for exploring mass transport limitations in SVE. Our group has done modeling work investigating the simulation of diffusion/desorption kinetics and the rate of nonaqueous phase liquid (NAPL) droplet solution (5–7) in SVE. Another factor which can limit the efficiency of SVE is the pneumatic permeability of the porous medium. If the permeability is highly variable, it is impossible to maintain an adequate flow of air through the domains of low permeability without maintaining an unacceptably large flow rate of air through the system. We explored this point earlier in connection with low-permeability lenses in a highly permeable matrix (8) and with families of permeabilities represented by Fourier series with randomly selected phases (9).

In the present paper we build on Roberts's work (9); we examine a number of sets of soil gas streamlines in the vicinity of a buried horizontal slotted pipe SVE well, we explore the variations in the progress of the clean ups for sets of permeability functions which are equivalent in a statistical sense, we investigate briefly the relatively small impact of variations in the concentration distribution of the contaminant VOC, and lastly we examine the quite large impact on remediation times of allowing the VOC to spread from the initial zone of contamination to a larger volume.

This model was analyzed and coded independently of our earlier work to serve as an independent check of that work. The notation and the methods used are essentially the same as were used by Roberts, to whose paper (9) the reader is referred for details; complete details of the analysis and a listing of the computer source code are provided in Bolick's thesis (10).

THEORY

Gas Flow

We shall model the situation in which a series of long horizontal slotted pipes are laid parallel to each other at constant interval and constant depth. Neglecting end effects permits us to deal with a two-dimensional problem;

we focus on a single one of the horizontal SVE pipes in the array. The notation and geometry are given in Fig. 1. Under conditions of steady gas flow in an isothermal porous medium, the equation for the soil gas pressure P in the vicinity of the well is

$$\nabla \cdot \mathbf{K} \nabla P^2 = 0 \tag{1}$$

where **K** is the pneumatic permeability tensor, assumed to be of the form

$$\mathbf{K} = \begin{pmatrix} K_x(x, y) & 0 \\ 0 & K_y(x, y) \end{pmatrix} \tag{2}$$

Boundary conditions are as follows: Along the top surface of the soil $(y = L_y)$:

$$P^2(x, L_y) = P_a^2 = 1 \text{ atm}^2 \tag{3}$$

if the surface is not covered by an impermeable strip; in regions where an impermeable strip is present, the boundary condition is replaced by the no-flow boundary condition

$$\partial P^2(x, L_y)/\partial y = 0 \tag{4}$$

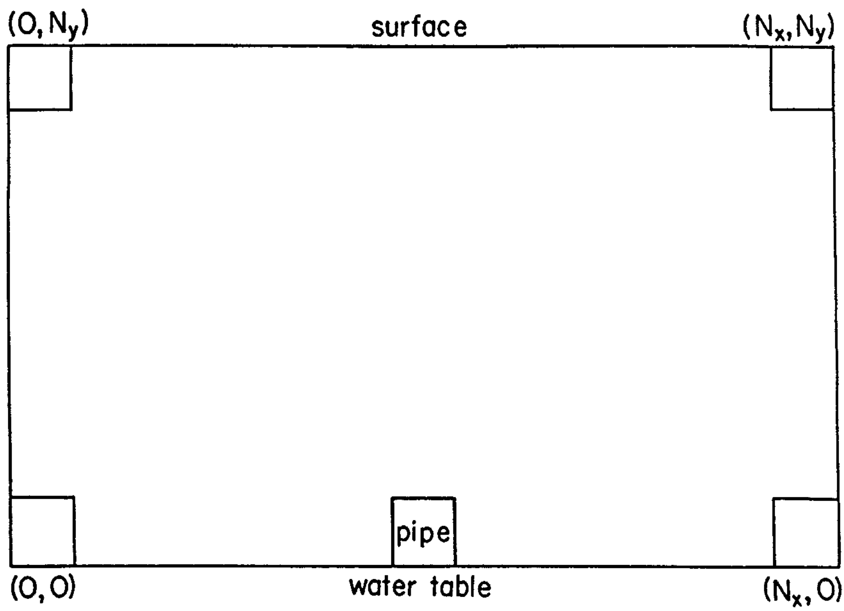

FIG. 1 Geometry and notation for the SVE model.

Along the left and right borders of the domain (located halfway between adjacent pipes), we assume a no-flow boundary condition, given by Eqs. (5) and (6):

$$\partial P^2(0, y)/\partial x = 0 \tag{5}$$

$$\partial P^2(L_x, y)/\partial x = 0 \tag{6}$$

Note that these boundary conditions are only approximate since the permeability is variable; the boundaries should be placed sufficiently far from the well that gas flow in the boundary regions is minimal. At the bottom of the domain we again use a no-flow boundary condition,

$$\partial P^2(x, 0)/\partial y = 0 \tag{7}$$

Lastly, we must include a boundary condition which represents the well. This is done as follows. In the near vicinity of the horizontal pipe, the gas pressure can be assumed to follow

$$(1/r)d/dr[rdP^2/dr] = 0 \tag{8}$$

where r is the radial distance away from the pipe. Integration of Eq. (8) twice then yields

$$P^2(r) = C_1 \log_e(r) + C_2 \tag{9}$$

The values of C_1 and C_2 are determined by requiring that

$$P^2(a) = P_w^2 \tag{10}$$

and

$$P^2(b) = P_a^2 \tag{11}$$

where P_a = ambient atmospheric pressure, atm
P_w = wellhead pressure, atm
a = radius of gravel packing of well, m
b = distance from the pipe to the soil surface, m

The value of b is taken to be

$$b = (N_y - J_{\text{well}} + 0.5)\Delta y \tag{12}$$

where J_{well} is the vertical coordinate index of the volume element containing the well pipe. See Fig. 1.

Calculation of C_1 and C_2 from the boundary condition requirements then yields

$$P^2(r) = P_w^2 + \left[\frac{P_a^2 - P_w^2}{\log_e(b/a)}\right] \log_e(r/a) \tag{13}$$

A mean square pressure in the volume element containing the well is then calculated by Eq. (14):

$$\langle P^2 \rangle = \int_0^c P^2(r)rdr / \int_0^c rdr \tag{14}$$

where $c = (\Delta x + \Delta y)/2$. Integration then yields

$$\langle P^2 \rangle = P_a^2 + \left[\frac{P_a^2 - P_w^2}{(c^2 - a^2)\log_e(b/a)} \right] \times \{c^2[\log_e(c/b) - 1/2] - a^2[\log_e(a/b) - 1/2]\} \tag{15}$$

The partial differential equation (Eq. 1) is approximated by means of a set of finite difference equations, modifications are introduced to include the boundary conditions discussed above, and the gas pressure in the volume element containing the SVE well pipe is calculated from Eq. (15). The difference equations are then solved by an overrelaxation method. The procedures have been described previously (6, 8, 10), so will not be repeated here.

The soil gas velocity field is then calculated from Darcy's law in the form

$$v_x(x, y) = -K_x(x, y)\partial P/\partial x \tag{16}$$

$$v_y(x, y) = -K_y(x, y)\partial P/\partial x \tag{17}$$

The soil gas streamlines and transit times can be computed by integration of Eqs. (16) and (17). The derivatives were calculated in terms of the pressure values at the grid points by means of a Taylor's series method, modified appropriately to take into account the boundary conditions; this is described in detail in the references mentioned.

Permeabilities

In this work the function for the soil pneumatic permeability components was taken to be the Fourier series investigated by Roberts (9). For the x-component of the permeability we take

$$K_x(x, y) = K_{x0} + \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} A_{mn} \cdot \sin(m\pi x/L_x + \psi_{mn}) \cdot \sin(n\pi y/L_y + \phi_{mn}) \tag{18}$$

where K_{x0} = mean x-component of the permeability, m^2/s atm
L_x = length of the contaminated area (at right angles to the pipe), m

L_y = depth of the contaminated area, m
ψ_{mn}, ϕ_{mn} = randomly selected phase angles, 0 to 2π
A_{mn} = amplitude coefficient, m^2/s atm

The A_{mn} were calculated from a minor variation of Roberts's prescription,

$$A_{mn} = (1/2)K_{x0}/(m^2 + n^2)^c, \qquad C < 0.5 \tag{19}$$

The Fourier function for $K_y(x, y)$ was calculated in a similar manner.

The model used for soil vapor extraction assumes a linear isotherm (an effective Henry's constant) and local equilibrium; such a model should show the effects of permeability variations most clearly. The modeling equation used was

$$\partial C^{\text{tot}}/\partial t = -\nu\nabla\cdot(vC^g) \tag{20}$$

where C^{tot} = total concentration of the VOC at the point (x, y), kg/m^3
ν = air-filled soil porosity
v = soil gas linear velocity at (x, y), m/s
C^g = soil gas VOC concentration, kg/m^3 of vapor phase

Also,

C^w = aqueous phase VOC concentration, kg/m^3 of aqueous phase
ω = water-filled soil porosity
K_H = effective Henry's constant of VOC, dimensionless

Then

$$C^{\text{tot}} = \nu C^g + \omega C^w \tag{21}$$

$$= [\nu + (\omega/K_H)]C^g \tag{22}$$

so Eq. (20) can be rewritten as

$$\frac{\partial C^{\text{tot}}}{\partial t} = -\frac{\nu}{\nu + (\omega/K_H)}(vC^{\text{tot}}) \tag{23}$$

The effects of dispersion were modeled by means of the numerical dispersion resulting from the numerical solution of the set of ordinary differential equations used to represent Eq. (23) over the same mesh used to calculate the soil gas pressures.

The total mass of VOC remaining in the domain of interest is then calculated from Eq. (24):

$$M_{\text{tot}}(r) = \sum_i \sum_j C_{ij}^{\text{tot}} \Delta x \Delta y \tag{24}$$

RESULTS

Isotropic Permeability Functions

We first examine the results obtained from a set of 17 runs made with isotropic permeability functions having random phase variations. The parameter set for these runs is given in Table 1.

We take Run 1 as the reference run; in it K_x and K_y were held constant at 0.100 m^2/s atm throughout the entire domain. The streamlines and transit times (in thousands of seconds) for this run are shown in Fig. 2. As will be seen later, this rather uniform distribution of gas flow results in one of the faster clean-up rates.

We briefly discuss four other runs of this set. The streamlines and transit times for Run 10 are shown in Fig. 3; this run produced the shortest 99.9% clean-up time. The only visible perturbations in the streamlines are rather minor variations near the outer edges of the domain, and the transit times are quite similar to those of the reference run (Fig. 2).

In Run 11, shown in Fig. 4, there is a region of quite low permeability in the left-central portion of the domain. As we shall see, the clean-up rate is not adversely affected because the gas flow displaced by this low-permeability domain is deflected partially into the lower left corner of the domain, where the soil gas generally moves quite slowly.

In Run 4 (Fig. 5), low-permeability regions exist all along the left side of the domain, as evidenced by the rather long gas transit times for the

TABLE 1
Default Parameters for Runs 1–17, for Which the Permeability Is Isotropic

Length of contaminated area	13 m
Depth of contaminated area	8 m
Δx, Δy	1 m
Coordinates of well	(6, 0) m
Wellhead pressure	0.85 atm
Packed radius of the well pipe	0.10 m
Temperature	273 K
Air-filled porosity of soil	0.2
Water-filled porosity of soil	0.3
VOC effective Henry's constant	0.005
Soil density	1.7 g/cm^3
Initial contaminant concentration	100 mg/kg
K_{x0}, K_{y0}	0.100 m^2/s atm
Upper bound for K_x, K_y	0.3 m^2/s atm
Lower bound for K_x, K_y	0.005 m^2/s atm
C (exponent in equation for A_{mn})	0.5

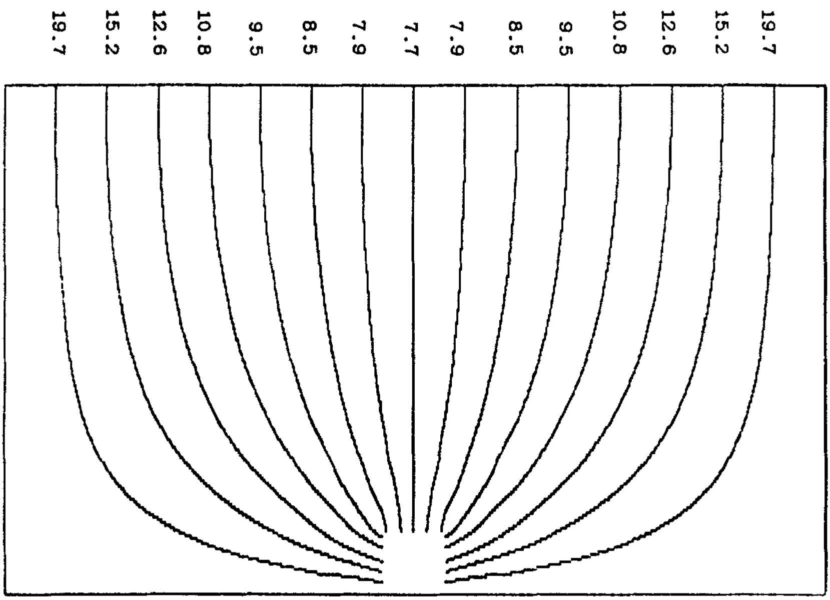

FIG. 2 Streamlines for Run 1, the case of constant permeability. The numbers above the streamlines represent the transit times in thousands of seconds. See Tables 1 and 2 for parameters.

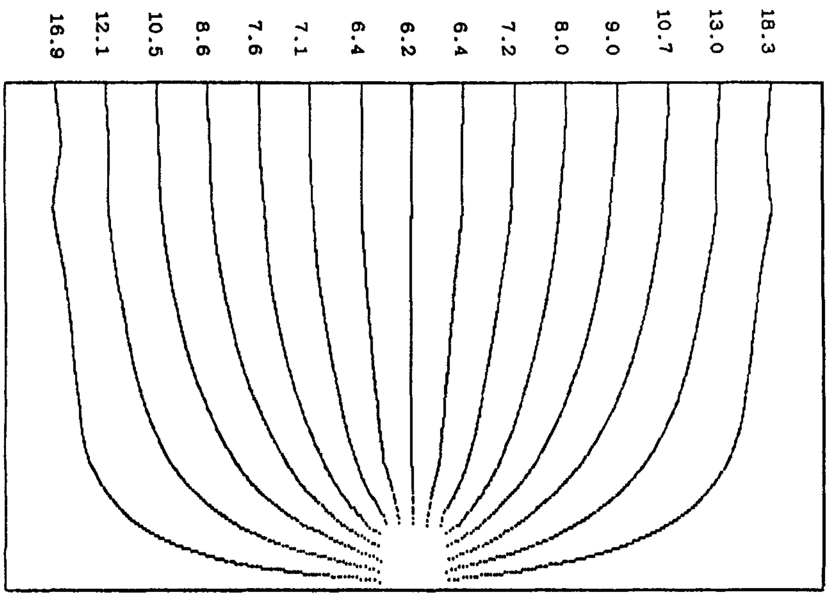

FIG. 3 Streamlines and transit times for Run 10. Parameters are given in Tables 1 and 2.

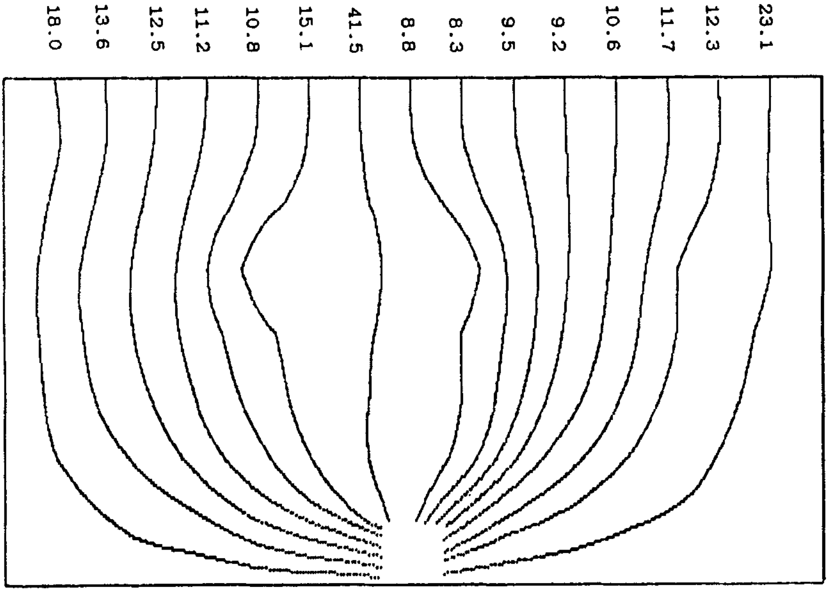

FIG. 4 Streamlines and transit times for Run 11. See Tables 1 and 2 for parameters.

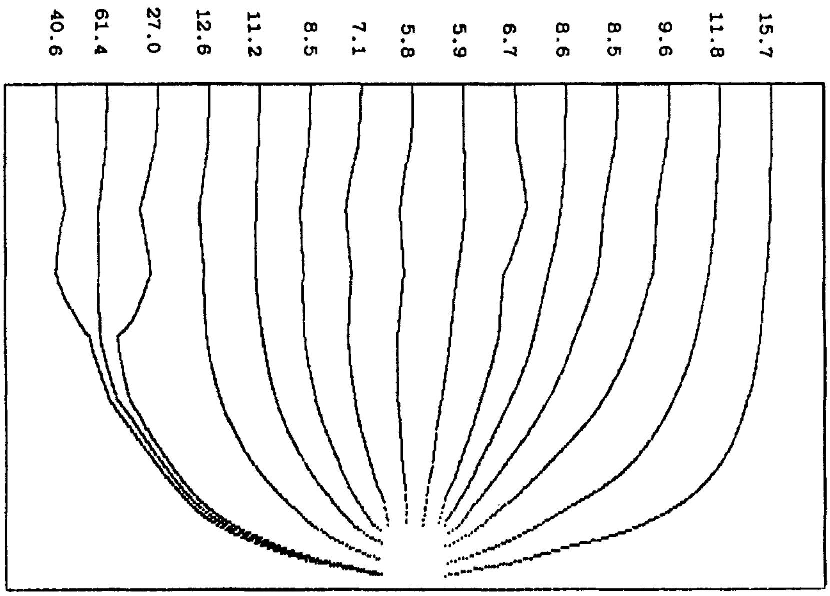

FIG. 5 Streamlines and transit times for Run 4. Parameters are given in Tables 1 and 2.

streamlines on the left side of the domain. Not surprisingly, we shall find a rather slow rate of clean up for this run.

The longest 99.9% clean-up time for this series of runs was observed for Run 9, streamlines and transit times for which are shown in Fig. 6. The transit time for the streamline on the far right of the domain is quite long, and the shape of the streamline indicates that there is a substantial volume on that side of the domain which will be cleaned up quite slowly. Actually, after a simulated 93 days of SVE, 55% of the contaminant originally present in the volume element in the lower right corner had not yet been removed.

The plots of residual VOC mass versus time for Runs 1–17 are shown in Figs. 7–10. Ten of the seventeen runs yielded 99.9% clean-up times of 70 to 90 days, in relatively good agreement with Run 1, the reference run. Clean-up times of 90 to 130 days were observed for Runs 4, 8, 13 and 16. In Run 4 the left portion of the domain was slow to clean up, but the volume element in the lower left corner received a sufficient flow of gas that it was cleaned up fairly expeditiously. In Run 8 the region of somewhat slow contaminant removal was along the water table in the lower left portion of the domain. Run 13 showed lower clean-up rates along the

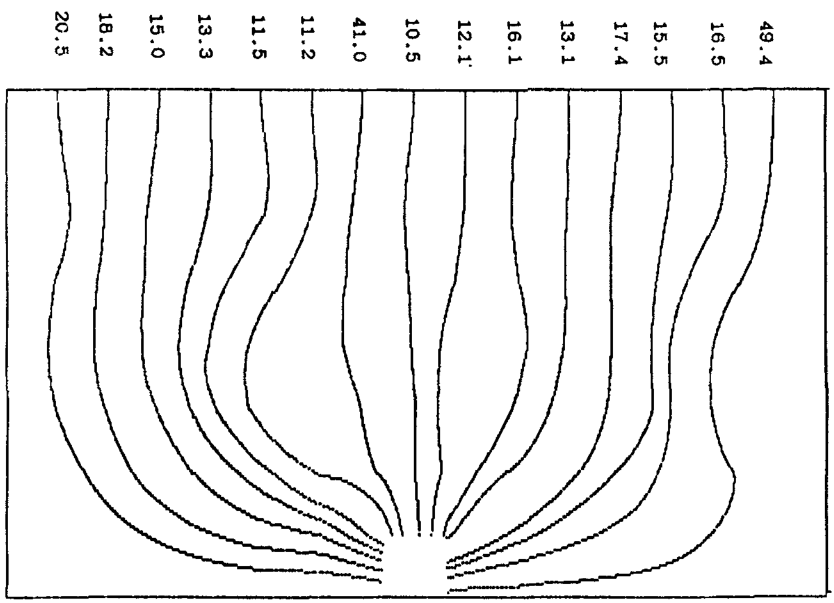

FIG. 6 Streamlines and transit times for Run 9. Parameters are given in Tables 1 and 2.

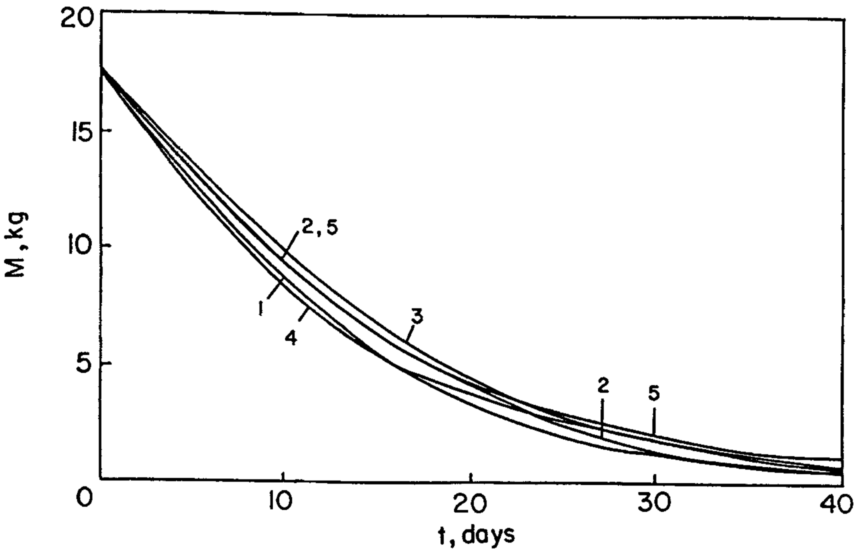

FIG. 7 Plots of residual contaminant mass M (in kg) versus time (in days) for Runs 1 through 5.

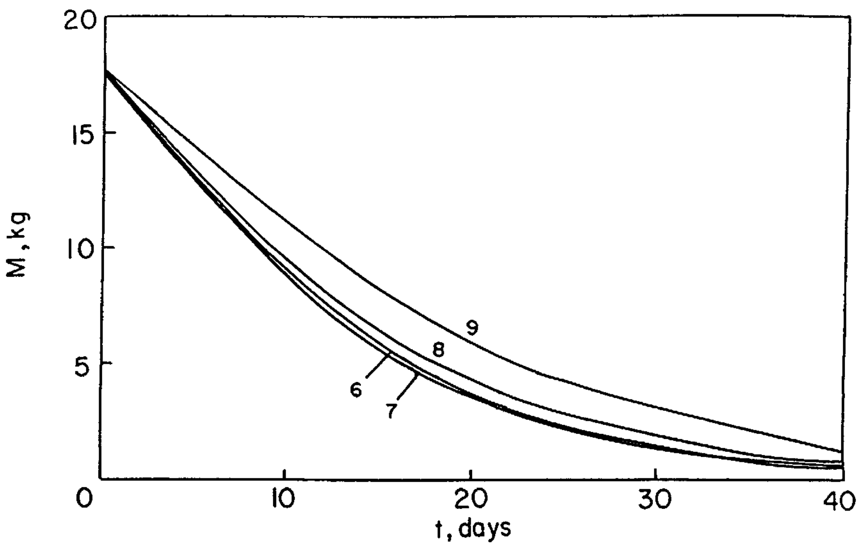

FIG. 8 Plots of mass versus time for Runs 6 through 9.

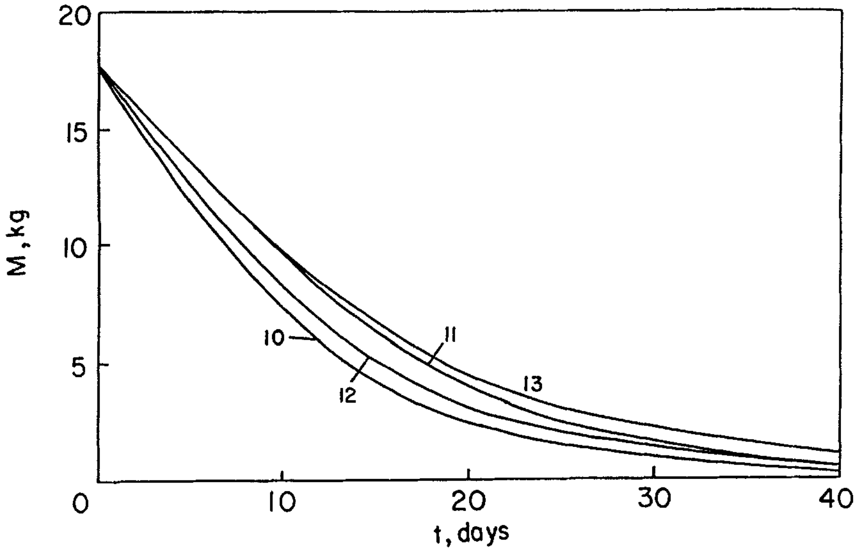

FIG. 9 Plots of mass versus time for Runs 10 through 13.

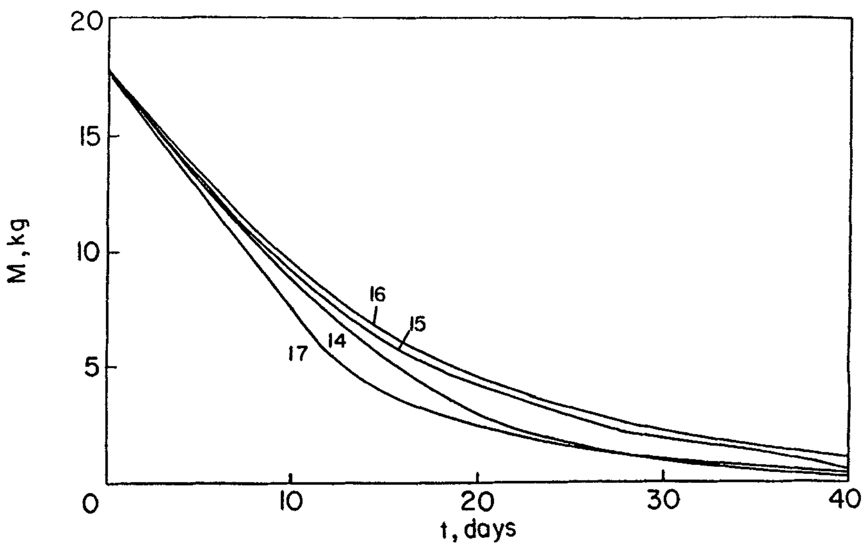

FIG. 10 Plots of mass versus time for Runs 14 through 17.

water table and in the vicinity of the right boundary, and Run 16 showed a slight decrease in clean-up rate in the lower right corner.

Three of the runs showed extremely long clean-up times, in the range of 170–190 days. These runs showed very slow rates of clean up in the volume element in the lower right corner. Evidently low permeabilities in regions near the outer lower portions of the domain of influence of the well are very damaging, and such configurations should be avoided if at all possible.

The 99.9% clean-up times for Runs 1–17 are given in Table 2, together with statistical data for these runs.

The data indicate rather substantial variations in the clean-up times; more detailed examination of the results shows that long clean-up times are associated with low permeabilities near the outer boundaries of the domain of influence, particularly near the water table. If the logs of test borings indicate the permeabilities are likely to be highly variable, it may be advisable to carry out borings at the outer boundaries of the proposed domains of influence of the wells and to relocate wells where the relationship between the well position and the location(s) of low-permeability domains is such that clean up may be prolonged.

TABLE 2
Clean-up Times for Runs 1–17, Isotropic Permeabilities

Run number	99.9% Clean-up time (days)
1 (reference run)	73.76
2	79.60
3	89.71
4	121.07
5	182.75
6	76.62
7	82.13
8	97.30
9	186.02
10	69.48
11	77.96
12	88.31
13	111.02
14	69.57
15	76.89
16	111.41
17	177.84

Arithmetic mean clean-up time = 104.20 days
Range of clean-up times: 69.48–186.02 days
Standard deviation of the clean-up time = 38.96 days

Anisotropic Permeabilities

A second set of 17 runs was carried out using the same random seeds (for generating the phase angles in the permeabilities) as were used in the first set. In the second series the horizontal component of the permeability was approximately three times greater than the vertical component, and the lower bounds for K_x and K_y were reduced from $K_{x0}/20$ and $K_{y0}/20$ (for the first set of runs) to $K_{x0}/30$ and $K_{y0}/30$ (for the second set of runs). The standard parameter set for the second series of runs is given in Table 3.

In this series the shortest 99.9% clean-up time occurs in the run in which the permeability components were constant ($K_x = 0.3$, $K_y = 0.1$). The streamlines and transit times for this run are shown in Fig. 11. These can be compared to those in Fig. 2, where K_x and K_y are constant and equal.

In Run 28 (Fig. 12) the same phase angles were used as in Run 11 (Fig. 4). The streamlines in Run 28 show a greater tendency to move laterally to avoid regions of lower permeability, and the transit times of most of the streamlines have been decreased. One, however, has been quite substantially increased, which results in an increase in the clean-up time for this run as compared to Run 11.

The longest clean-up time for the second series of runs is found for Run 34, streamlines and transit times for which are shown in Fig. 13. The streamline on the far right has an extremely long transit time (18 times

TABLE 3
Standard Parameter Set for Runs 18–34, Anisotropic Permeabilities

Length of domain	13 m
Depth of domain	8 m
Δx, Δy	1 m
Well coordinates	(6, 0) m
Wellhead pressure	0.85 atm
Packed radius of well	0.10 m
Temperature	273 K
Air-filled porosity	0.20
Water-filled porosity	0.30
Effective Henry's constant	0.005
Soil density	1.7 g/cm^3
Initial contaminant concentration	100 mg/kg
K_{x0}, K_{y0}	0.300, 0.100 m^2/s atm
Upper bound for K_x, K_y	0.900, 0.300
Lower bound for K_x, K_y	0.010, 0.0033
C (exponent for A_{mn} term in K_x)	0.40
D (exponent for A_{mn} term in K_y)	0.43

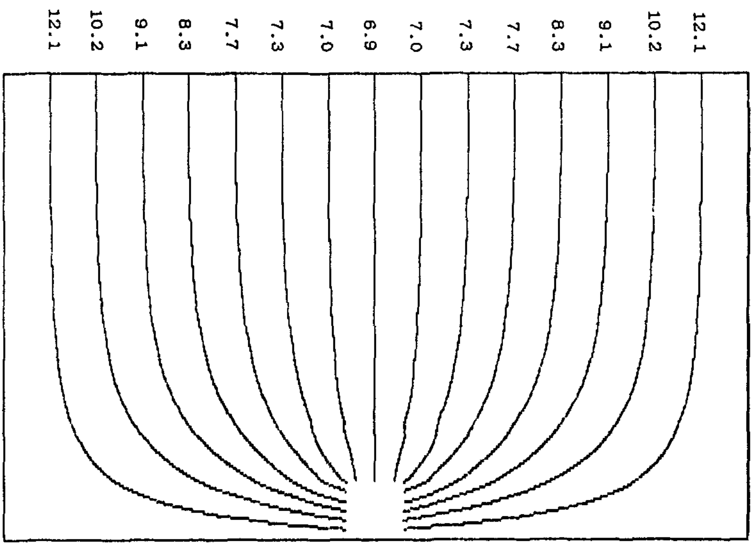

FIG. 11 Streamlines for Run 18, the case of constant permeability. Parameters are given in Tables 3 and 4. Compare with Run 1, Fig. 2.

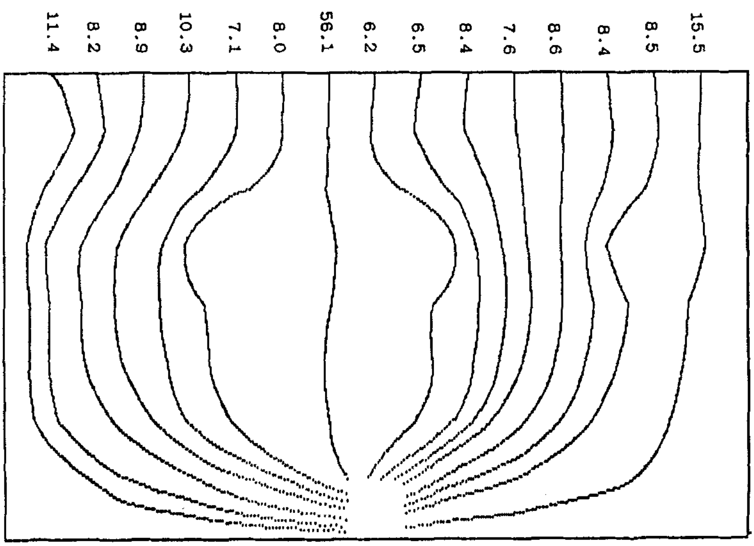

FIG. 12 Streamlines for Run 28. Parameters are given in Tables 3 and 4. Compare with Run 11, Fig. 4.

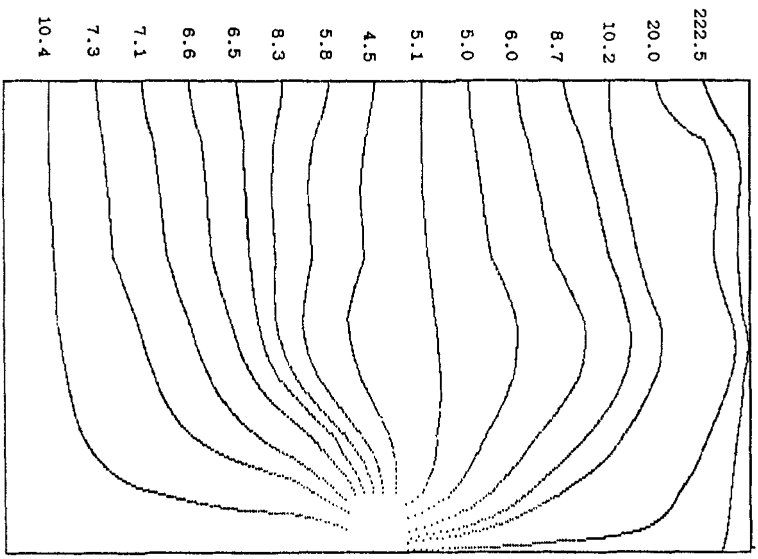

FIG. 13 Streamlines for Run 34. See Tables 3 and 4 for parameters.

longer than that of the corresponding streamline in Run 18 (the run with constant permeabilities). As mentioned earlier, this is an example of poor well placement with regard to regions of low permeability, and one should expect a long clean-up time.

The plots of residual VOC mass versus time for Runs 18–34 are shown in Figs. 14–17. These runs are described in the same order as in the first series, so that Run 18 has the same set of phase angles as Run 1, Run 19 has the same set of phase angles as Run 2, etc. Seven of these runs have 99.9% clean-up times in the range 30–60 days; in these runs there are generally only relatively minor deviations of the permeability components from K_{x0} and K_{y0}.

Runs 24, 33, 20, and 31 have clean-up times in the range 60–90 days. In Runs 24 and 33, low-permeability regions exist in the lower right portion of the domain, but the permeability in the lower right volume element is not low, so clean up is not severely delayed. Runs 20 and 31 have areas of moderately low permeability in the vicinity of the well, resulting in some increase in clean-up time.

Six runs show clean-up times in excess of 100 days. Run 21 shows slow removal in the left central region near the boundary of the domain of influence. Run 28 has very low permeability in the near vicinity of the well, which drastically reduces gas flow. In Run 30 there are regions of

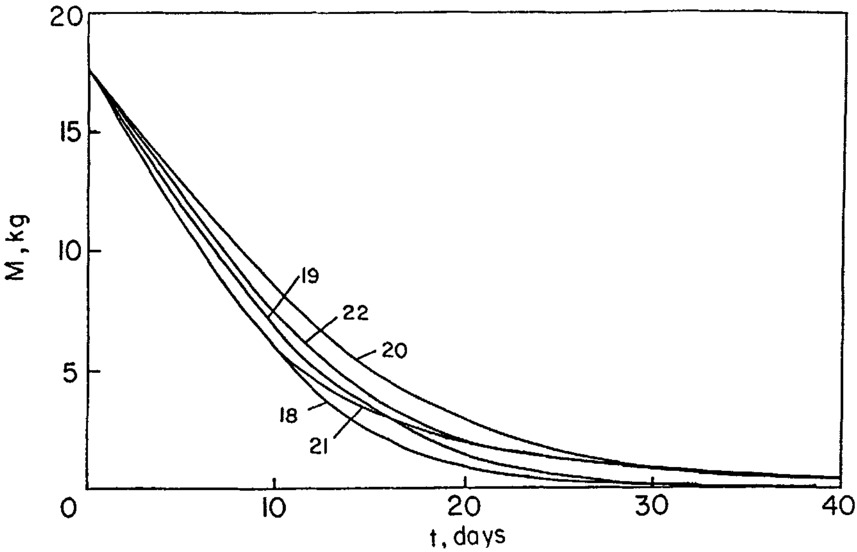

FIG. 14 Plots of mass versus time for Runs 18 through 22. Compare with Runs 1 through 5, Fig. 7.

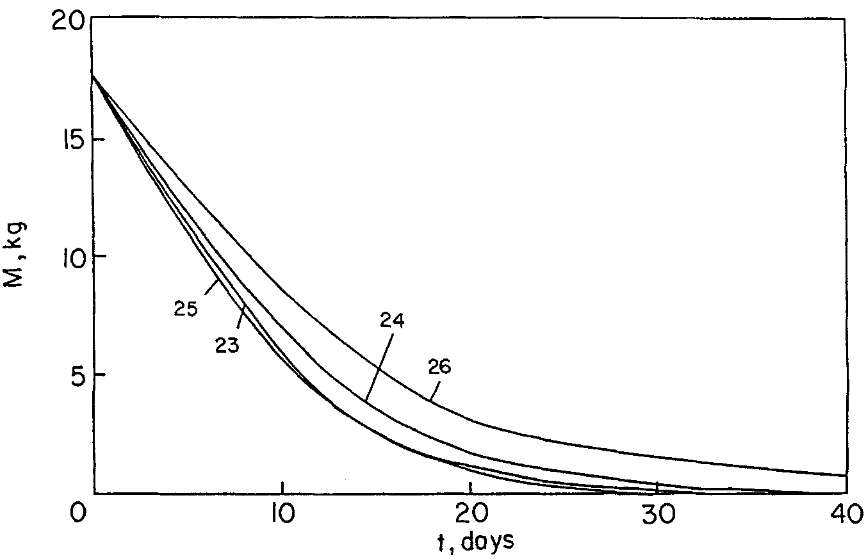

FIG. 15 Plots of mass versus time for Runs 23 through 26. Compare with Runs 6 through 9, Fig. 8.

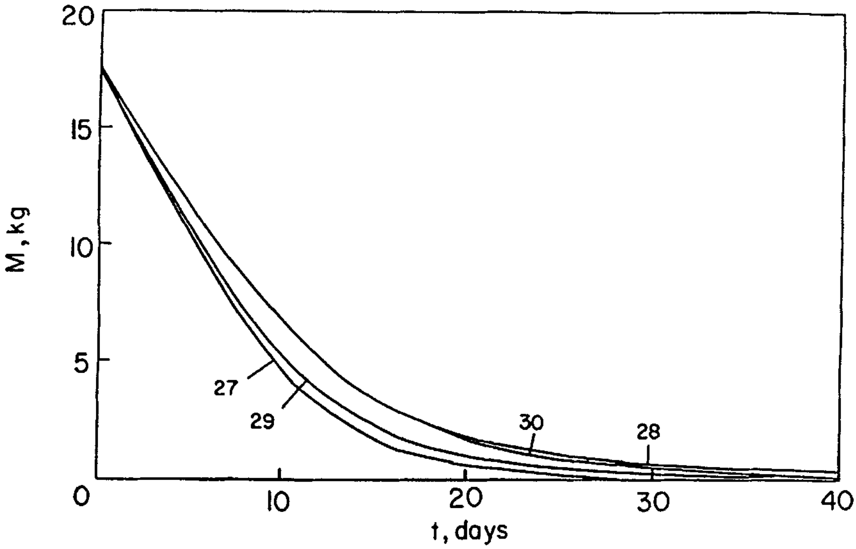

FIG. 16 Plots of mass versus time for Runs 27 through 30. Compare with Runs 10 through 13, Fig. 9.

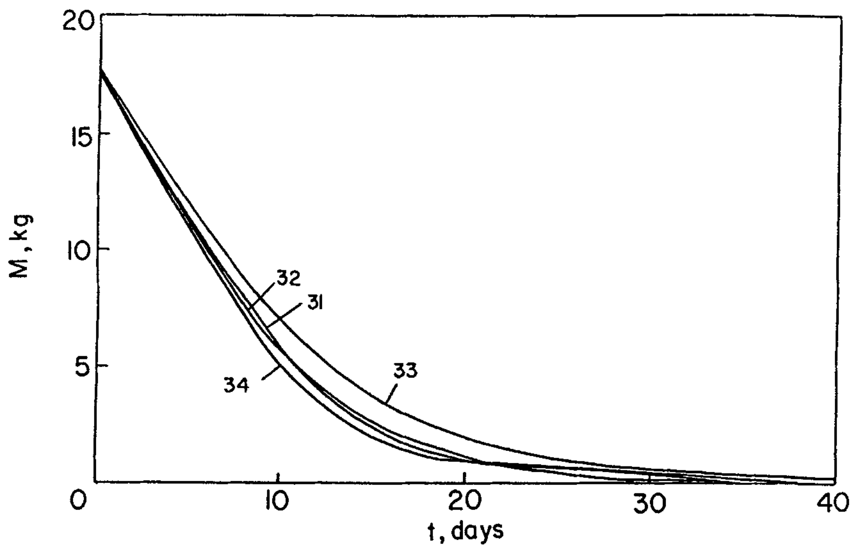

FIG. 17 Plots of mass versus time for Runs 31 through 34. Compare with Runs 14 through 17, Fig. 10.

quite low permeability in the upper right and upper left corners of the domain of influence. Runs 22, 26, and 34 show the longest clean-up times. In all three of these runs the lower right corner of the domain has low permeability, so that clean up of this region is extremely slow.

A summary of Runs 18–34 is given in Table 4. In this series the mean 99.9% clean-up time is 79.08 days, compared to the value of 104.20 days for the first set (which has the smaller value of K_{x0}). The standard deviation of the clean-up time for these runs is over 50% of the mean value. Again we find that the longest clean-up times are generally associated with low permeabilities in the lower corners of the domains.

The data from these runs indicate that there is a quite substantial uncertainty associated with vapor stripping model calculations if the permeability is highly variable and the locations of the regions of low permeability are not fairly well known.

Effects of Random Variations in the Initial VOC Concentration

The effects of random variations in the initial VOC concentrations were also explored. The initial concentrations of VOC in the various volume

TABLE 4
Summary of Runs 18–34, Anisotropic Permeabilities

Run number	99.9% Clean-up time (days)
18 (constant K_x, K_y)	37.88
19	43.92
20	76.99
21	108.64
22	123.74
23	39.20
24	62.70
25	50.51
26	131.05
27	38.19
28	109.78
29	50.04
30	103.46
31	87.35
32	39.71
33	63.56
34	177.65

Mean 99.9% clean-up time = 79.08 days
Range of clean-up time: 37.88–177.65 days
Standard deviation = 39.71 days

elements were calculated from Eq. (25):

$$C_{\text{init}} = C_0 + (-1)^u \cdot C_{\text{vary}} \cdot Rnd \tag{25}$$

where C_0 = base concentration, 100 mg/kg in these runs
$u = 5 \cdot \text{CINT}[C_{\text{vary}} \cdot Rnd)$
C_{vary} = maximum allowable concentration variation, mg/kg
Rnd = value produced by random number generator, uniformly distributed on (0, 1)
CINT(x) = integer closest in value to x
C_{init} = initial VOC concentration to be assigned to a volume element

Three of the runs from the second series (with anisotropic permeabilities) were used in this analysis. For each of these runs, calculations were performed with maximum allowable concentration variations of 5, 10, 20, 50, and 100 mg/kg. Other run parameters are as in Table 3. Tables 5 and 6 provide listings of initial concentrations for the volume elements in two of the runs.

A summary of the results is given in Table 7. Runs 35–39 have the same permeability function as Run 32, which gave a clean-up time of 39.71 days. The maximum variation of the clean-up time from that for Run 32 is 0.42%, in Run 38. Runs 40–44 have the same permeability function as Run 20, which gave a clean-up time of 76.99 days. The maximum variation in clean-up time from that of Run 20 in these runs is 1.1%, in Run 44. Runs 45–49 have the same permeability function as Run 22, which had a 99.9% clean-up time of 123.74 days. The maximum variation from this value is 2.4%, seen for Run 49.

The results of this rather brief study suggest that spatial variations in the concentration are of rather minor importance, provided that the overall

TABLE 5
Initial Concentration for Each Element in Run 36 Allowable Concentration Range = 90 to 110 ppm (average initial concentration = 100.59 ppm)

102	109	99	96	107	99	101	102	102	96	98	99	110
104	98	99	110	110	104	91	103	107	104	110	104	93
93	109	96	94	100	104	110	91	108	106	102	110	95
94	99	107	95	107	109	109	93	94	102	99	95	107
101	107	102	95	100	98	107	93	96	102	91	95	104
94	100	94	105	96	91	109	108	90	101	98	106	106
91	102	105	104	107	92	101	98	101	100	104	92	103
104	99	100	104	91	95	103	107	95	104	92	92	104

TABLE 6
Initial Concentration for Each Element in Run 44 Allowable Concentration Range = 50 to 150 ppm (average initial concentration = 95.87 ppm)

55	141	87	62	97	107	86	50	100	83	88	89	99
90	58	132	116	143	122	69	102	136	57	54	133	101
139	56	132	86	90	94	51	51	126	117	82	61	101
86	85	123	64	89	82	59	75	71	122	137	79	131
55	117	140	107	124	89	51	132	84	79	73	129	134
139	95	91	106	114	88	143	112	64	144	70	52	85
122	75	57	96	51	131	84	68	120	66	138	87	53
58	123	138	102	141	56	86	114	78	126	128	57	148

size of the contaminated domain is reasonably accurately known. This is in marked contrast to the effects of variations in the permeability.

Effects of Swift Intervention Using SVE

All of the runs described here so far have had the contaminant VOC distributed throughout the entire domain of influence of the SVE well.

TABLE 7
Summary of Runs 35–49 with Random Concentration Variations

Run	Random seed for concentration	Maximum variation (ppm)	t(99.9%) (days)	Percent variation
32	—	0	39.71	—
35	−3333	5	39.70	0.02
36	−4747	10	39.79	0.18
37	−9176	20	39.77	0.13
38	−7324	50	39.55	0.42
39	−3624	100	36.07	0.11
20	—	0	76.99	—
40	−3223	5	76.94	0.07
41	−9183	10	77.27	0.36
42	−13268	20	76.96	0.04
43	−27	50	77.82	1.07
44	−1234	100	76.16	1.09
22	—	0	123.74	—
45	−23332	5	123.27	0.38
46	−30000	10	122.27	1.19
47	−16324	20	122.84	0.72
48	−3636	50	126.01	1.83
49	−15831	100	120.78	2.39

One would expect that clean-up times (and costs of remediation) might be significantly reduced if SVE could be initiated before the contaminant had spread throughout the entire domain. The set of runs to be presented here roughly simulates the results of SVE intervention at various times after an initial spill, as the extent to which the VOC has spread increases. We consider a given fixed quantity of VOC which is initially distributed in one of the four regions indicated in Fig. 18. Region 1 corresponds to a time very shortly after the spill; Region 4 to a rather long time after the spill has occurred, so that the VOC has had opportunity to spread quite widely. In our modeling, Region 1 contains six volume elements; Region 2, twenty; Region 3, forty-two; and Region 4, seventy-two.

Three permeability functions which had yielded runs having widely differing clean-up times were chosen for use in exploring the effects of starting remediation at various times after the spill. Run 18 had a constant, anisotropic permeability function and a domain with VOC distributed uniformly throughout; it yielded a 99.9% clean-up time of 37.88 days. Runs 50–53 correspond to this system with the same quantity of VOC distributed in Regions 1, 2, 3, and 4, respectively. The plots of mass versus time for these runs are shown in Fig. 19. The clean-up times were 2.80, 7.70, 17.74, and 23.17 days, respectively.

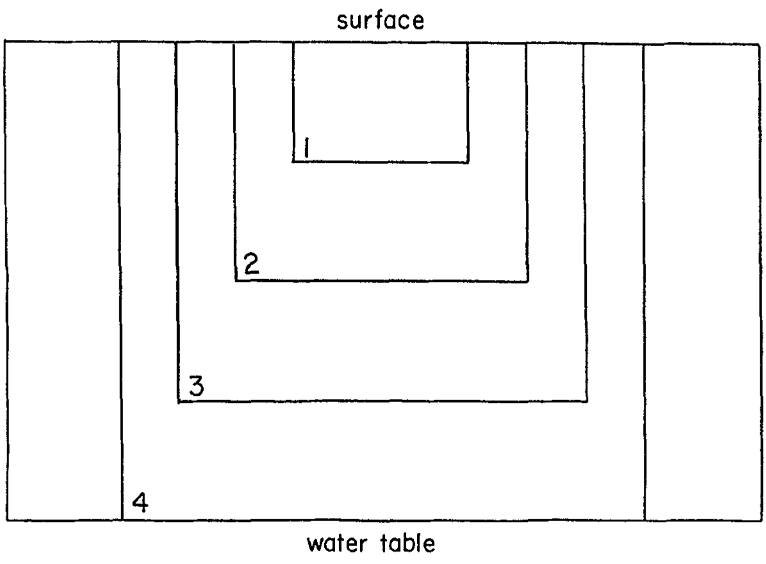

FIG. 18 Schematic showing the distributions (Regions 1, 2, 3, and 4) of contaminant VOC used in Runs 50–61.

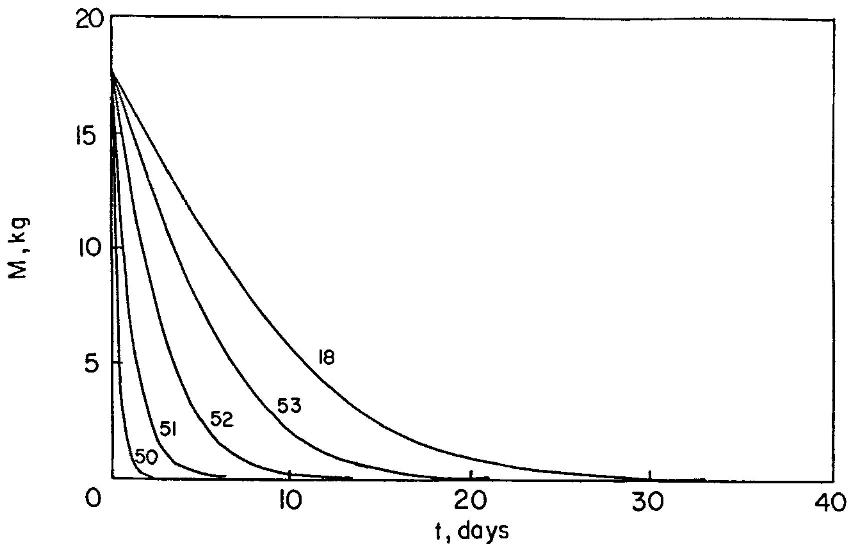

FIG. 19 Plots of total contaminant mass versus time for Runs 18 and 50–53.

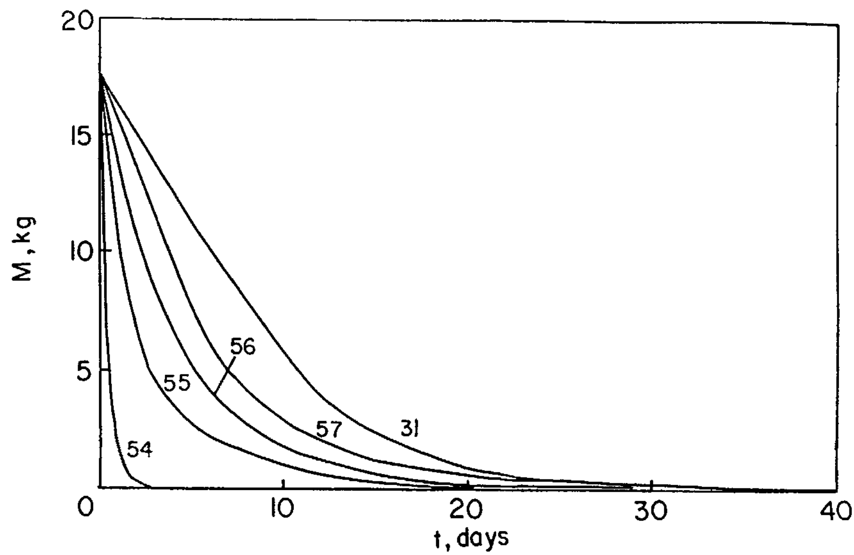

FIG. 20 Plots of total contaminant mass versus time for Runs 31 and 54–57.

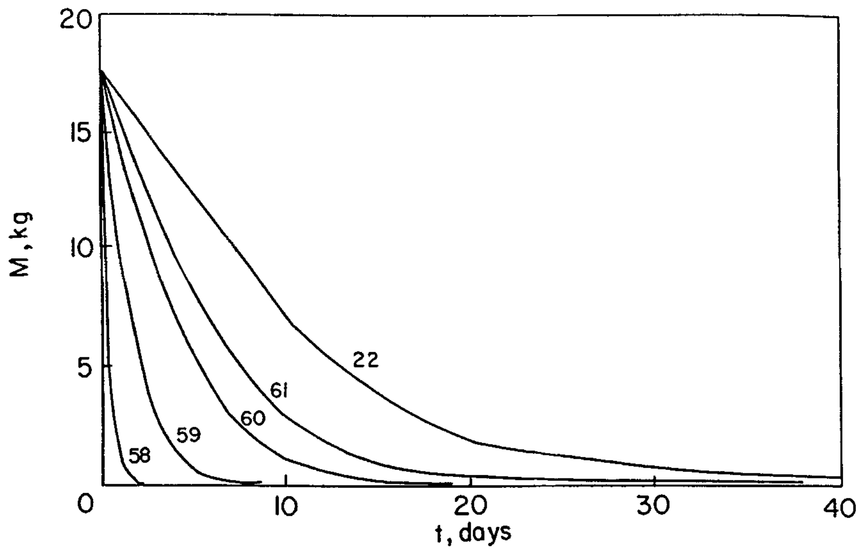

FIG. 21 Plots of total contaminant mass versus time for Runs 22 and 58–61.

Run 31 in the previous series (anisotropic permeability, VOC spread uniformly throughout the entire domain) had a clean-up time of 87.35 days. Runs 54–57, shown in Fig. 20, show the results for this system when the VOC is initially distributed in Regions 1, 2, 3, and 4, respectively. The 99.9% clean-up times for these runs were 3.43, 28.90, 36.63, and 64.56 days, respectively.

Run 22 was one of the worst cases in the second series of runs with anisotropic variable permeabilities in which the VOC was spread uniformly throughout the domain, with a clean-up time of 123.74 days. Runs 58–61 were made for this system with the VOC initially distributed in Regions 1, 2, 3, and 4, respectively; see Fig. 21. The clean-up times for these runs were 2.74, 10.15, 25.37, and 47.04 days, respectively.

CONCLUSIONS

First, these results indicate that if there are large uncertainties in the value of the permeability as a function of position, there will inevitably be large uncertainties in the calculated clean-up time.

Second, clean-up times will be particularly slow if the soil in the outer lower portions of the domain of influence is of low permeability or if the well itself is screened in a region of low permeability so that the gas flow rate of the well is small. Logs of test borings may be helpful in trying to avoid these unfavorable situations.

Third, the distribution of contaminant VOC within a given volume of contaminated soil appears to have substantially less effect on clean-up times than do variations in the permeability. This suggests that increased emphasis on permeability measurements and decreased emphasis on the measurement of soil VOC concentrations might be in order. It is certainly necessary, however, to make enough VOC measurements to map out the extent of the contamination.

Fourth, runs made in which the same mass of contaminant is distributed in volumes of soil ranging from relatively small to relatively large indicate that clean-up times by SVE can be greatly reduced by the earliest possible intervention. These model runs suggest that if preliminary pumping were started immediately, before lengthy contract negotiations and before all regulatory questions had been resolved, one might reduce or avoid groundwater contamination and would greatly accelerate the timetable for complete remediation of the site.

REFERENCES

1. U.S. EPA, *Cleaning up the Nation's Waste Sites: Markets and Technology Trends*, U.S. EPA Report EPA/542/R-92/012, April 1993, pp. 18–19.
2. T. A. Pedersen and J. T. Curtis, *Soil Vapor Extraction Technology Reference Handbook*, U.S. EPA Report EPA/540/2-91/003, February 1991.
3. S. Feenstra and R. J. C. Hennet, "Assessment of Performance Limitations on Soil Vapor Extraction (SVE) in Variable Soils," personal communication.
4. D. C. DiGiulio, J. S. Cho, R. R. Dupont, and M. W. Kemblowski, "Conduction Field Tests for Evaluation of Soil Vacuum Extraction Application," in *Proceedings of the 4th National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods*, Las Vegas, Nevada, May 14–17, 1990, p. 587.
5. D. J. Wilson, "Soil Clean Up by *in-situ* Aeration. V. Vapor Stripping from Fractured Bedrock," *Sep. Sci. Technol.*, *25*, 243 (1990).
6. D. J. Wilson, C. Gomez-Lahoz, and J. M. Rodriguez-Maroto, "Mathematical Modeling of SVE: Effects of Diffusion Kinetics and Variable Permeabilities," in *Proceedings, Symposium on Soil Venting*, April 29–May 1, 1991, Houston, Texas; U.S. EPA Report EPA/600/R-92/174, September 1992.
7. D. J. Wilson, "Soil Clean Up by *in-situ* Aeration. XIII. Effects of Solution Rates and Diffusion in Mass-Transport-Limited Operation," *Sep. Sci. Technol.*, *29*, 579 (1994).
8. C. Gomez-Lahoz, J. M. Rodriguez-Maroto, and D. J. Wilson, "Soil Clean Up by *in-situ* Aeration. VI. Effects of Variable Permeabilities," *Ibid.*, *26*, 133 (1991).
9. L. A. Roberts and D. J. Wilson, "Soil Clean Up by *in-situ* Aeration. XI. Cleanup Time Distributions for Statistically Equivalent Variable Permeabilities," *Ibid.*, *28*, 1539 (1993).
10. J. J. Bolick Jr., "The Effects of Random Permeability Variations on Soil Vapor Stripping Model Calculations," M.S. Thesis, Submitted to Vanderbilt University, July 21, 1993.

Received by editor August 2, 1993