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Removal of Semivolatiles from Soils by Steam Stripping. I. A Local Equilibrium Model

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Abstract

A mathematical model for the *in-situ* steam stripping of volatile and semivolatile organics from contaminated vadose zone soils at hazardous waste sites is developed. A single steam injection well is modeled. The model assumes that the pneumatic permeability of the soil is spatially constant and isotropic, that the adsorption isotherm of the contaminant is linear, and that the local equilibrium approximation is adequate. The model is used to explore the streamlines and transit times of the injected steam as well as the effects of injection well depth and contaminant distribution on the time required for remediation.

INTRODUCTION

Soil vapor extraction (SVE) has turned out to be a quite useful technique for the remediation of vadose zone soils contaminated with volatile organics, but is limited to compounds having sufficiently high vapor pressures at the temperature of the soil to permit cleanup in a reasonable period of time. As the vapor pressure decreases the efficiency of the process drops off, becoming marginal when the vapor pressure is 0.5 torr; see Pedersen and Curtis (*1*). The technique is therefore ineffective against fuel oils, diesel fuel, kerosene, polynuclear aromatic hydrocarbons, PCBs, etc. Vapor pressures of organic compounds typically increase by a factor of roughly 4 for every 10°C rise in temperature, which has suggested to a number of workers that the use of steam might be effective in removing these compounds of reduced volatility from contaminated soils. The U.S. EPA considers steam injection as a "developing" technology for hazardous waste site remediation (*2*). Ghassemi (*3*) and Houthoofd et al. (*4*) recently reviewed a number of thermal remediation technologies.

In hot air/steam enhanced stripping, hot air and/or steam is injected into the soil, allowed to move through the contaminated domain, and then removed together with the mobilized volatile and semivolatile contaminants. The resulting gas stream and condensate must then be further treated; these residuals treatments (with demisters, condensers, scrubbers, chillers, activated carbon, catalytic oxidation units, etc.) are relatively well established technologies (*1*).

Dong and Bozzelli (*5*) presented a gas chromatographic technique for determining adsorption parameters and enthalpies of adsorption for VOCs on soils over a wide range of temperatures. These authors also developed an unusually complete and detailed theoretical analysis of the processes taking place in the soil columns in the gas chromatograph (advection, axial dispersion within the soil column, inter- and intraparticle diffusion, mass transport through the film around the soil particles, adsorption–desorption equilibrium, and heat of adsorption) which they used in interpreting their data and which should be quite useful as a research tool in laboratory studies. The complexity of the model raises some question as to the feasibility of its extension in all details to problems in two dimensions and its use on the types of microcomputers which are available to most environmental engineers.

Dong and Bozzelli's chromatographic technique appears to provide a convenient and accurate method for investigating adsorption of VOCs on soils, relevant to both steam stripping and soil vapor extraction. It provides a tool by which a lot of data on a variety of soils and VOCs over a wide range of temperatures can be obtained quickly and cheaply. Temperature dependences of adsorption parameters are of particular interest in steam stripping or if the soil is to be heated by other means.

Dong and Bozzelli provided data on several chlorinated VOCs (chloroform, methylene chloride, carbon tetrachloride, and 1,1,1-trichloroethane) and aromatics (benzene, toluene, chlorobenzene, and 1,2,4-trichlorobenzene) sorbed on thoroughly baked soils. The data included adsorption isotherm parameters, enthalpies of adsorption, mass transfer parameters, and minimum allowable temperatures for complete desorption. The adsorption isotherm parameters were highly temperature dependent. One hopes that this technique can be used on moist soils as well as dry soils, and that data on the adsorption and mass transfer kinetics of VOCs in moist soils will be reported in the future, since these would be of great interest to people working in soil vapor extraction.

One of the major studies of *in-situ* steam stripping is the work carried out for EPA by Lord and his associates at Drexel University (*6–11*). This group has carried out both lab scale experimental work and theoretical work. In laboratory studies they explored the effects of contaminant vapor pressure and polarity; of the proportions of sand, silt, clay, and organic matter (topsoil); and of steam pressure on removal rates. The effect of vapor pressure is that, as expected, decreasing vapor pressures (increasing normal boiling points) result in lower rates of removal for the series octane, decane, dodecane, as well as for butanol and octanol. All these compounds, however, as well as kerosene, were found to steam strip at reasonable rates. The presence of silt, clay, and natural organic material was found to decrease the rate of removal by steam stripping, due both to decreased flow rates of steam and apparently to adsorption processes. Increased steam pressure, resulting in increased steam flow rates, yields more rapid removals, although excessive pressures may result in fracturing of the soil and short circuiting.

These workers found virtually complete removal of kerosene from contaminated sand by 126 pore volumes of steam, and also observed removal of dodecane from sand (5% by weight initially) down to about 0.016% by steam stripping at 11.5 psi over a period of 6 h. They found that steam stripping of soil initially dried at 500°C and then spiked was more rapid than vacuum stripping, air stripping, and simple heat stripping; the applicability of these results in the field may be questionable, however, because the very rigorous initial drying of the soil may have removed water from adsorption sites which are occupied by water (and therefore not available to sorb organics) under natural conditions. Greatly increased binding of VOCs by extremely dry soils and the release of these sorbed VOCs in the presence of moisture has been observed in soil vapor stripping operations (*1*).

These workers presented a mathematical model for steam stripping in their first paper (*8*) which they used in interpreting experimental results and in estimating the results of scaled up steam stripping operations. They noted in a later paper (*6*), however, that the model had been criticized as having some problems, and that they were working on a revision. We discuss briefly a few of these problems in the following.

The model assumes that soil gas pressures in the vicinity of a steam injection well can be calculated by a suitably constructed solution to the Laplace equation

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

which is applicable to noncompressible fluids. For gases which may be treated as following the ideal gas law $PV = nRT$, the correct equation (for a constant, isotropic permeability, and an isothermal system) is

$$\nabla^2 P^2 = 0 \tag{2}$$

If the soil gas pressures are all nearly 1 atm, little error results from the use of Eq. (1); however, in steam stripping, steam pressures of the order of 10 psi are apparently quite probable, and steam pressures as high as 50 psi have been mentioned, so one can expect significant errors to be introduced at times by this approximation.

The method of images was used to obtain a solution to Laplace's equation, but the image potential constructed (which uses a source and a single image) fails to satisfy the no-flow boundary condition which is applicable at the bottom of the vadose zone. If the steam is being injected well down in the vadose zone, reasonably near its lower boundary, this could be a significant source of error. This problem can be eliminated by a somewhat more elaborate array of sources (*12*), which makes subsequent formulas more complex but still quite manageable on microcomputers.

The bulk of the modeling analysis assumes that transport in the vapor phase is advective; in one section, however, the assumption is made that the steam flows are purely diffusive, which is inconsistent with the earlier discussion of the model. Given the steam pressures under consideration and the flow rates involved, one can probably conclude that diffusion is unimportant except within individual soil particles or within porous lumps of low-permeability material embedded in the soil being treated.

A mathematical model for steam stripping would be a very useful tool in doing site-specific assessments of technology feasibility, costs, system design, etc., and similar models have been used in soil vapor extraction to good advantage (*1*). We therefore felt that it would be useful to develop a model built on the pioneering work of Lord's group and on our own experience with soil vapor extraction models (Ref. *13*, for example), and which avoids some of the problems mentioned above. A first iteration at such a model is discussed in the following sections.

A STEAM STRIPPING MODEL

Streamlines and Vapor Transit Times

In steam stripping, as in soil vapor extraction, it is crucial that advecting gas be moved through the contaminated region of soil at a reasonable rate if satisfactory cleanup times are to be achieved. This makes the calculation of the soil gas streamlines and transit times from the point of steam injection to the surface of some interest. These matters are explored in this section.

At steady-state gas flow in an isotropic porous medium of spatially constant permeability, the soil gas pressure obeys the equation

$$\nabla^2 P^2 = 0 \tag{2'}$$

if the gas obeys the ideal gas law $PV = nRT$. The linear velocity of the gas is assumed to be given by Darcy's law,

$$\bar{v} = -k\nabla P \tag{3}$$

where k is the pneumatic permeability of the soil (m^2/atm·s) and P is in atmospheres.

The geometrical setup and some of the notation are given in Fig. 1. The boundary conditions to be satisfied by the solution to Eq. (2) are as follows:

$$P(r,h) = 1 \text{ atm} \qquad \text{(soil surface)} \tag{4}$$

$$\partial P(r,0)/\partial z = 0 \qquad \text{(bottom of vadose zone)} \tag{5}$$

Also, there must be a gas source at $(0,a)$ which supplies Q mol/s of steam.

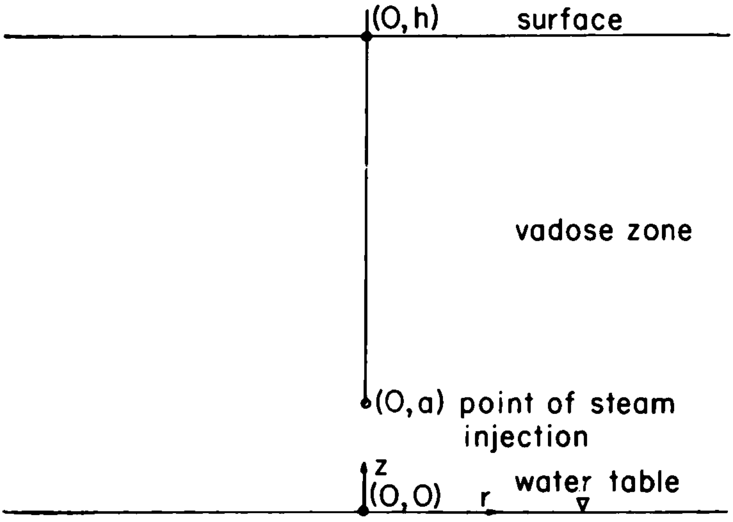

FIG. 1. Geometrical setup and notation for the calculation of the gas pressure distribution in the vicinity of a steam or hot air injection well.

This problem is readily solved by the method of images from electrostatics. Let

$$P^2 - 1 = W \tag{6}$$

Then it is readily seen from symmetry considerations that

$$W = A \sum_{n=-\infty}^{\infty} \left[\frac{1}{[r^2 + (z - 4nh - a)^2]^{1/2}} + \frac{1}{[r^2 + (z - 4nh + a)^2]^{1/2}} - \frac{1}{[r^2 + (z - (4n - 2)h - a)^2]^{1/2}} - \frac{1}{[r^2 + (z - (4n - 2)h + a)^2]^{1/2}} \right] \tag{7}$$

is a solution to Laplace's equation which vanishes at $z = h$, and that $\partial W/\partial z = 0$ when $z = 0$, so that $\partial P/\partial z$ satisfies Eq. (5).

The constant A is obtained by the requirement that the total gas flux from the well at $(0,a)$ be Q mol/s. We have

$$Q = \int_0^{\pi} \int_0^{2\pi} \nu v_\rho c(\rho) \rho^2 \sin\theta \, d\phi \, d\theta \tag{8}$$

where ρ is the radius in a spherical coordinate system centered at $(0,a)$, v_ρ is the radial component of the gas velocity, ν is the porosity of the soil, and $c(\rho)$ is the gas concentration (mol/m^3) a distance ρ from the gas source. Now $c(\rho) = P(\rho)/RT$, and we have $2P\nabla P = \nabla W$ from Eq. (6). In the near vicinity of the source the potential W is essentially A/ρ, so $\partial W/\partial\rho = -A/\rho^2$. Substituting for $c(\rho)$ in Eq. (8) then yields

$$Q = \int_0^{\pi} \int_0^{2\pi} \nu \left[-k \frac{\partial P}{\partial \rho} \right] \frac{P(\rho)}{RT} \rho^2 \sin\theta \, d\phi \, d\theta \tag{9}$$

Since $\nabla P = \nabla W/2P$, on substituting in Eq. (9) and integrating we obtain

$$Q = \frac{2\pi\nu k A}{RT} \tag{10}$$

so

$$A = \frac{RTQ}{2\pi\nu k} \tag{11}$$

We are using SI units, so R, the gas constant, is equal to 8.206×10^{-5} $\mathrm{m^3{\cdot}atm/mol{\cdot}deg}$.

Thus W is given by

$$W = P^2 - 1 = \frac{RTQ}{2\pi\nu k} \sum_{n=-\infty}^{\infty} \left[\frac{1}{[r^2 + (z - 4nh - a)^2]^{1/2}} + \frac{1}{[r^2 + (z - 4nh + a)^2]^{1/2}} - \frac{1}{[r^2 + (z - (4n - 2)h - a)^2]^{1/2}} - \frac{1}{[r^2 + (z - (4n - 2)h + a)^2]^{1/2}} \right] \tag{12}$$

The gas velocity components are obtained from Eq. (3); they are

$$v_r = \frac{-k}{2P}\frac{\partial W}{\partial r} \tag{13}$$

and

$$v_z = \frac{-k}{2P}\frac{\partial W}{\partial z} \tag{14}$$

where $P = (W + 1)^{1/2}$.

The derivatives in Eqs. (13) and (14) are

$$\frac{\partial W}{\partial r} = \frac{RTQr}{2\pi\nu k} \sum_{n=-\infty}^{\infty} \left[-\frac{1}{[r^2 + (z - 4nh - a)^2]^{3/2}} - \frac{1}{[r^2 + (z - 4nh + a)^2]^{3/2}} + \frac{1}{[r^2 + (z - (4n - 2)h - a)^2]^{3/2}} + \frac{1}{[r^2 + (z - (4n - 2)h + a)^2]^{3/2}} \right] \tag{15}$$

and

$$\frac{\partial W}{\partial z} = \frac{RTQ}{2\pi\nu k} \sum_{n=-\infty}^{\infty} \left[-\frac{(z - 4nh - a)}{[r^2 + (z - 4nh - a)^2]^{3/2}} \right.$$

$$- \frac{(z - 4nh + a)}{[r^2 + (z - 4nh + a)^2]^{3/2}} + \frac{(z - (4n) - 2)h - a)}{[r^2 + (z - (4n - 2)h - a)^2]^{3/2}}$$

$$\left. + \frac{(z - (4n - 2)h + a)}{[r^2 + (z - (4n - 2)h + a)^2]^{3/2}} \right] \quad (16)$$

Streamlines and transit times are then obtained by integrating the parametric equations

$$dr/dt = v_r(r,z) \quad (17)$$

and

$$dz/dt = v_z(r,z) \quad (18)$$

from starting points (r_0,z_0) to such time t_f as $z(t_f) = h$—that is, the streamline reaches the surface of the soil. One can integrate in the reverse direction (from the soil surface down to the well) by using a negative value for the time increment in the numerical integrations. Generally we chose

$$r_0 = (h/10) \sin \theta_n \quad (19)$$

$$z_0 = a + (h/10) \cos \theta_n \quad (20)$$

$$\theta_n = n\pi/n_{\max}, \qquad n = 1, 2, \ldots, n_{\max} \quad (21)$$

where $n_{\max}$ is the number of streamlines to be plotted.

The model developed by Lord's group at Drexel uses a somewhat simpler method for calculating the gas flow fields, and we shall compare that approach with ours. In that method the gas is treated as incompressible, and the vadose zone is assumed to extend infinitely far below the well, which permits one to drop the boundary condition given by Eq. (4). If one uses this geometry with a compressible gas and employs the method of images, one obtains

$$P^2 - 1 = W$$

$$= \frac{RTQ}{2\pi\nu k}\left[\frac{1}{[r^2 + (z - a)^2]^{1/2}} - \frac{1}{[r^2 + (z - 2h + a)^2]^{1/2}}\right] \tag{22}$$

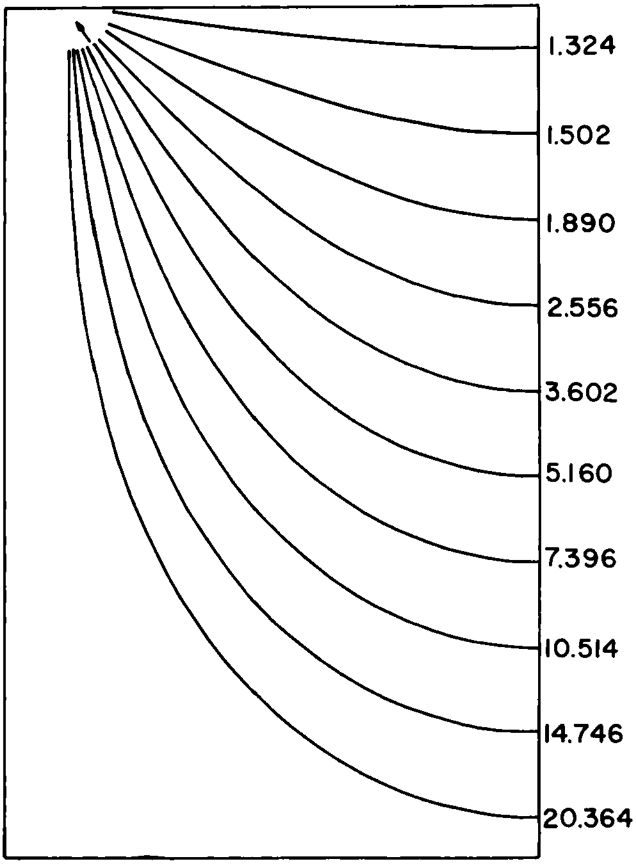

FIG. 2. Gas flow field and transit times for Lord's model, which assumes that the vadose zone extends to an infinite depth. Other parameters as in Fig. 3.

where $z = h$ at the soil surface and the well is at a depth of $h - a$. Then

$$\frac{\partial W}{\partial r} = \frac{RTQr}{2\pi\nu k}\left[\frac{-1}{[r^2 + (z - a)^2]^{3/2}} + \frac{1}{[r^2 + (z - 2h + a)^2]^{3/2}}\right] \tag{23}$$

and

$$\frac{\partial W}{\partial z} = \frac{RTQ}{2\pi\nu k}\left[\frac{-(z - a)}{[r^2 + (z - a)^2]^{3/2}} + \frac{(z - 2h + a)}{[r^2 + (z - 2h + a)^2]^{3/2}}\right] \tag{24}$$

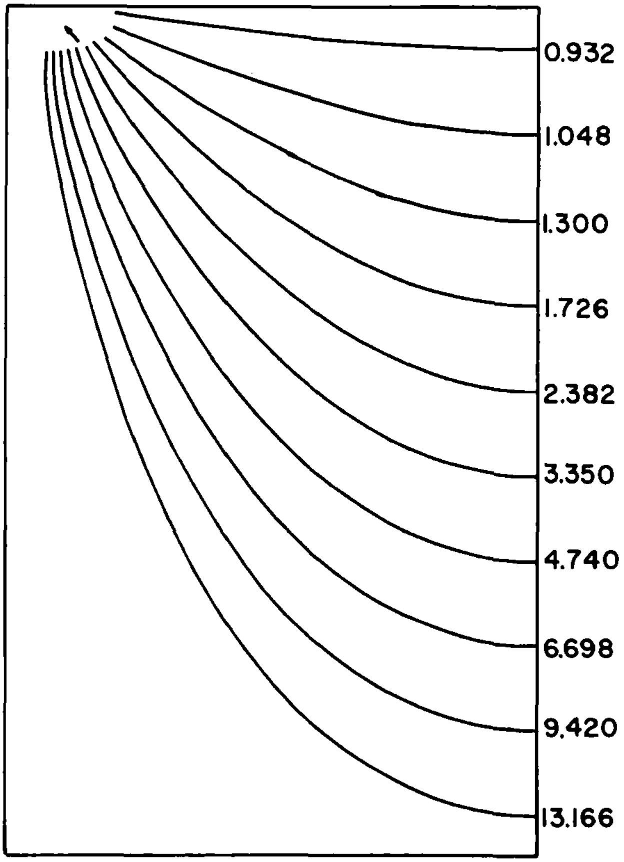

FIG. 3. Gas flow field and transit times for our model. Depth to water table = 8 m, depth of well = 7 m, domain radius = 12.8 m, permeability = 0.1 m^2/atm·s, porosity = 0.3, temperature = 100°C, rate of steam injection = 5 kg/h. Gas pressure 0.8 m from the steam source = 1.009 atm.

One then calculates v_r and v_z from Eqs. (13) and (14), and integrates Eqs. (17) and (18) as before to obtain the streamlines and transit times with this model.

If the well is discharging steam fairly near the bottom of the vadose zone, the two methods give significantly different flow fields and transit times, as seen by comparing Fig. 2 (obtained with our version of Lord's model) and Fig. 3 (obtained with our model, with the steam discharge at a depth of 7 m and the bottom of the vadose zone at a depth of 8 m). Gas transit times for similar streamlines differ by an order of 50%. The differences are less marked if the depth of the vadose zone is 16 m, as shown

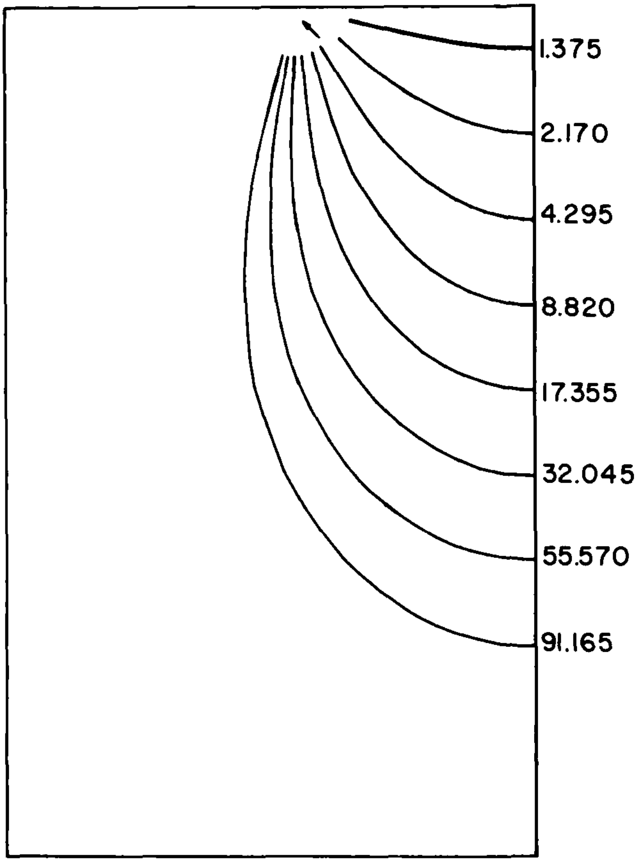

FIG. 4. Gas flow field and transit times for Lord's model, assuming that the point of steam discharge is at a depth of 7 m and that the vadose zone extends to an infinite depth. The domain size shown here has a depth of 16 m and a radius of 25.6 m. Other parameters as in Fig. 3.

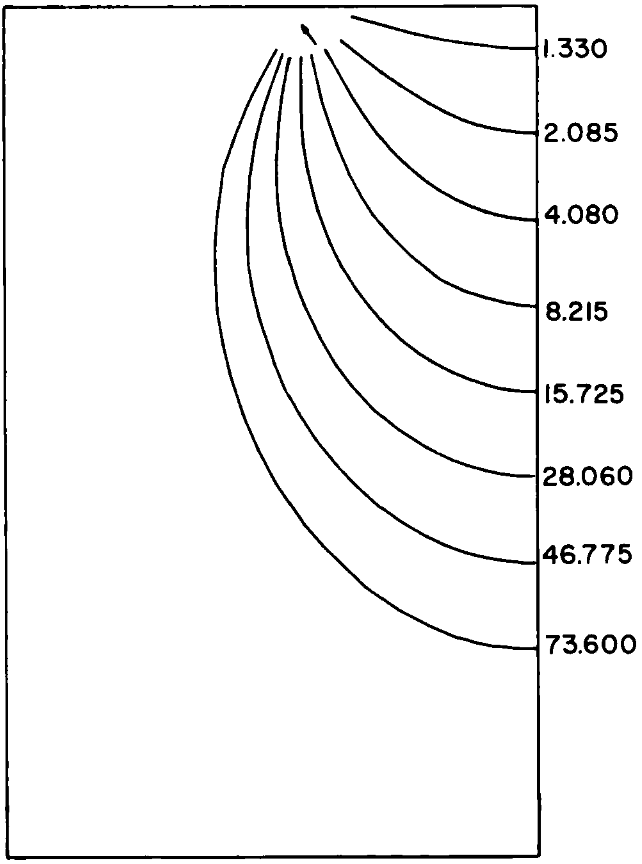

FIG. 5. Gas flow field and transit times for our model, assuming that the point of steam discharge is at a depth of 7 m and the vadose zone extends to a depth of 16 m. Domain radius = 25.6 m. Other parameters as in Fig. 3.

by a comparison of Fig. 4 (Lord's model) with Fig. 5 (ours); here the transit times for similar streamlines differ by an order of 10%.

If the gas is assumed incompressible and the steam flow rate Q (mol/s) is held constant, changes in the pneumatic permeability k can cause no changes in the transit times or the streamlines. If the gas obeys the ideal gas law, however, transit times are affected, as seen by comparing Fig. 3 (k = 0.1 m^2/atm·s) with Figs. 6, 7, and 8 (k = 0.01, 0.0025, and 0.001 m^2/atm·s, respectively). In all these runs the steam is being injected at a rate of 10 kg/h. The effects of gas compressibility become appreciable only when the absolute pressure of the steam in the well becomes significantly

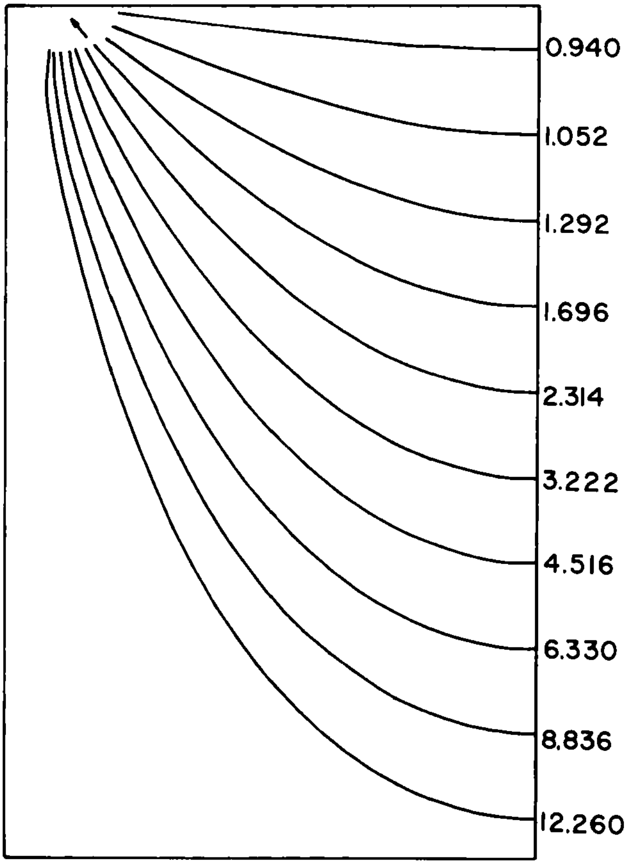

FIG. 6. Streamlines and transit times for our model (compressible gas) with pneumatic permeability = 0.01 m^2/atm·s. Other parameters as in Fig. 3. Gas pressure 0.8 m from the source = 1.086 atm.

larger than 1 atm, so for low steam pressures (about 1 atm) the assumption of incompressibility is not a bad approximation.

Local Equilibrium Model for Steam Stripping

The geometry and the notation are indicated in Fig. 9. We assume axial geometry, local equilibrium between the stationary (condensed phase) VOC and the moving vapor, and a linear isotherm with isotherm parameter K_H relating the contaminant concentration in the stationary phase(s) in the ijth volume element and the vapor phase concentration in this element,

$$c_{ij}^{g} = K_H c_{ij}^{s} \tag{25}$$

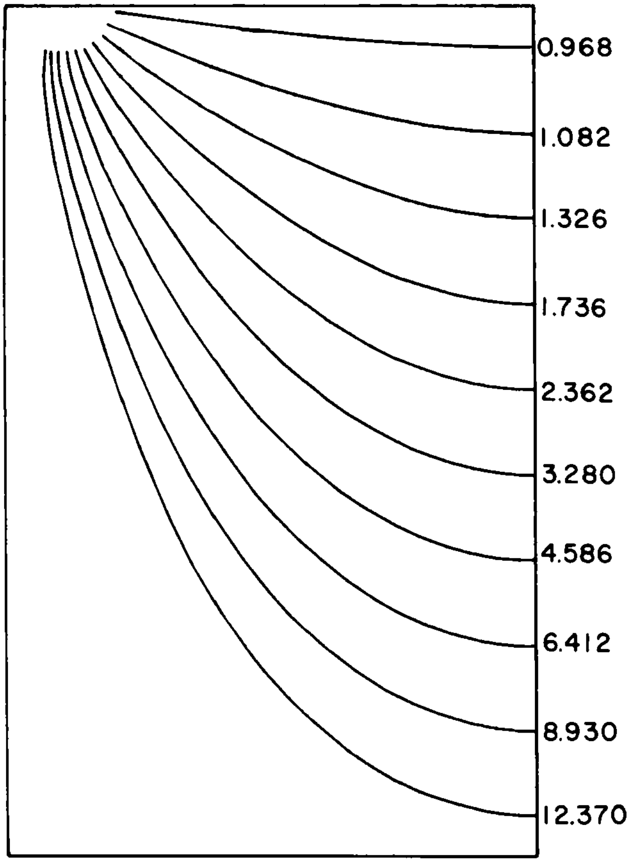

FIG. 7. Streamlines and transit times for our model, pneumatic permeability = 0.0025 $m^2/atm \cdot s$. Other parameters as in Fig. 3. Gas pressure 0.8 m from the source = 1.311 atm.

Concentrations are in kg/m^3 of soil (c^s) and kg/m^3 of gas phase (c^g).

Let

$$V_{ij} = (2i - 1)\pi(\Delta r)^2\Delta z = \text{volume of the } ij\text{th element}$$

$$m_{ij} = \text{contaminant mass in the } ij\text{th volume element}$$

Then

$$m_{ij} = V^{ij}(c^s_{ij} + \nu c^g_{ij}) = V_{ij}(1 + \nu K_{\mathrm{H}})c^s_{ij} \qquad (26)$$

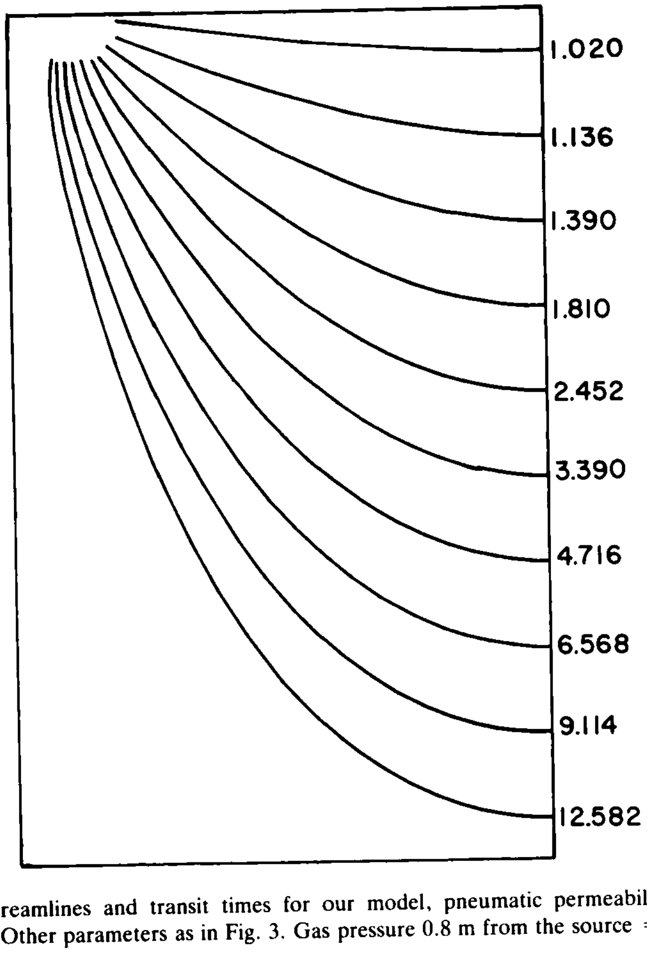

FIG. 8. Streamlines and transit times for our model, pneumatic permeability = 0.001 m^2/atm·s. Other parameters as in Fig. 3. Gas pressure 0.8 m from the source = 1.671 atm.

Let

$$v_{ij}^L = v_r[(i - 1)\Delta r, (j - 1/2)\Delta z] \tag{27}$$

$$v_{ij}^R = v_r[i\Delta r, (j - 1/2)\Delta z] \tag{28}$$

$$v_{ij}^U = v_z[(i - 1/2)\Delta r, j\Delta z] \tag{29}$$

$$v_{ij}^B = v_z[(i - 1/2)\Delta r, (j - 1)\Delta z] \tag{30}$$

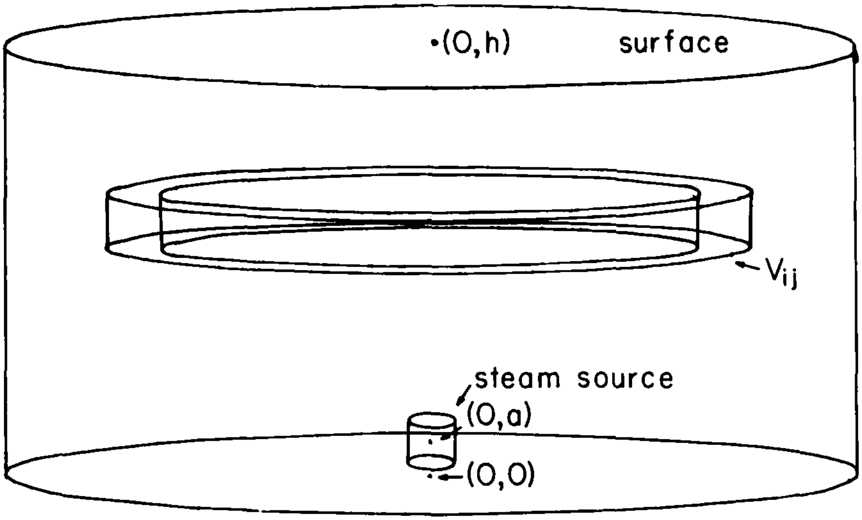

FIG. 9. Geometry and notation for the local equilibrium model for steam stripping.

where these velocities are calculated by means of this procedure described in the preceding section and are the velocities with which VOC is moved across the boundaries of the *ij*th volume element.

One then carries out a mass balance on the VOC in the *ij*th volume element; on using Eq. (26) this yields

$$\begin{aligned}\frac{dc_{ij}^{s}}{dt} = \frac{K_{\mathrm{H}}\nu\pi}{V_{ij}(1 + K_{\mathrm{H}})} 2(i - 1)\Delta r\Delta z v_{ij}^{L} c_{i-1,j}^{s} - 2i\Delta r\Delta z v_{ij}^{R} c_{ij}^{s} \\ + (2i - 1)(\Delta r)^2 v_{ij}^{B} S(v^{B}) c_{i,j-1}^{s} + (2i - 1)(\Delta r)^2 v_{ij}^{B} S(-v^{B}) c_{ij}^{s} \\ - (2i - 1)(\Delta r)^2 v_{ij}^{U} S(-v^{U}) c_{i,j+1}^{s} - (2i - 1)(\Delta r)^2 v_{ij}^{U} S(v^{U}) c_{ij}^{s} \quad (31)\end{aligned}$$

Here

$$\begin{aligned} S(x) &= 0 \quad \text{if} \quad x < 0 \\ &= 1 \quad \text{if} \quad x \geq 0 \end{aligned}$$

and

$$S(v^{B}) = S(v_{ij}^{B}), \text{ etc.}$$

In the set of Eqs. (31), boundary terms from outside the domain of interest are suppressed, and VOC is automatically exhausted through the surface of the soil. These equations were integrated numerically by a predictor-corrector method by means of a program written in TurboBASIC and run on an MMG 386 microcomputer with a math coprocessor and running at 33 MHz. A typical simulation required about an hour of machine time.

The effect of well depth on the removal is shown in Figs. 10 and 11; the default run parameters are given in Table 1. The zone of contamination is 16 m in diameter and extends to a depth of 3 m. The 99% cleanup time is affected relatively slightly by the depth of the steam injection well so long as the well penetrates completely through the zone of contamination. Substantial increases in 99% cleanup time occur, however, if the steam is injected above the bottom of the zone of contamination.

The effect of the extent to which the contaminant has spread laterally and vertically in the soil is shown in Fig. 12. Default model parameters are given in Table 1. In these runs the initial total mass of contaminant VOC is held constant, so that the initial contaminant concentration decreases as the volume of the zone of contamination increases. In all cases the point of steam injection is well below the bottom of the zone of contamination. The more widely and deeply the contaminant is spread, the longer the time required for cleanup. This is presumably due both to the lower vapor phase contaminant concentrations which can be achieved

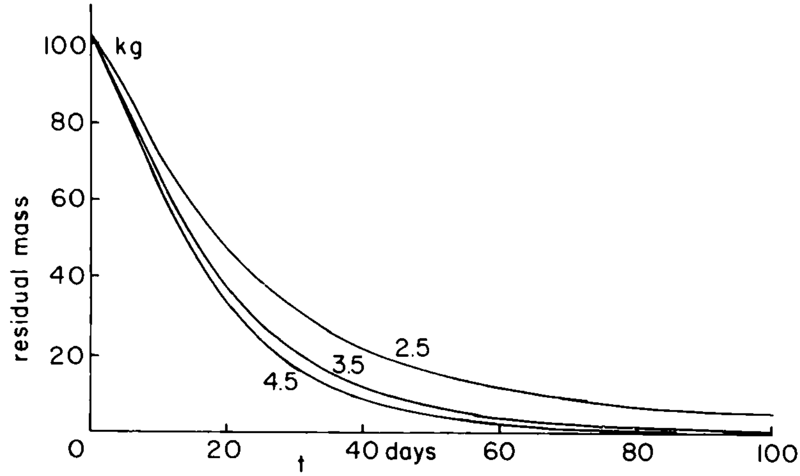

FIG. 10. The effect of shallow well depth on semivolatile contaminant removal, our model. Parameters as in Table 1. The zone of contamination is 16 m in diameter and extends to a depth of 3 m. The well depths (in meters) are indicated on the curves.

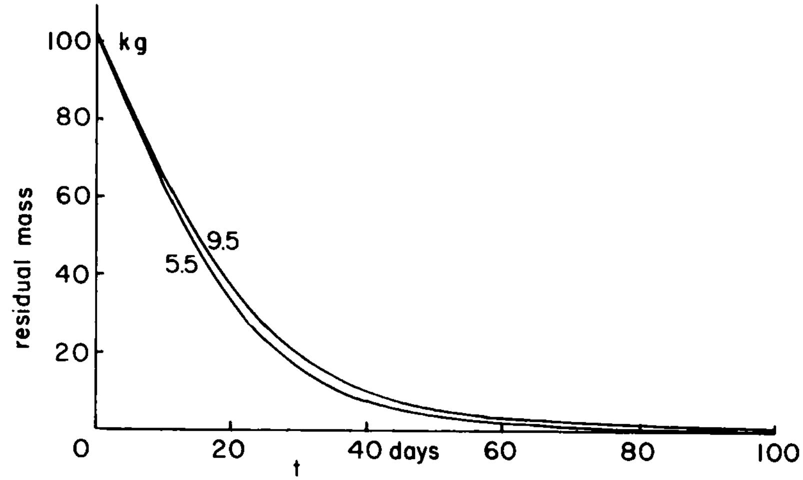

FIG. 11. The effect of deep well depth on semivolatile contaminant removal, our model. Parameters as in Table 1. The zone of contamination is as in Fig. 10, and the well depths (in meters) are indicated on the curves.

(since the condensed phase concentrations are lower) and to the movement of contaminant into more peripheral regions in the domain in which the gas velocities are reduced. This latter problem can be eliminated by the placement of additional wells, but this costs money. Evidently one would be well advised to begin remedial operations as soon as possible if there is any indication that the contaminant is still spreading either laterally or vertically.

TABLE 1
Default Model Parameters for the Steam Stripping Runs[a]

Depth to water table	10 m
Depth of well	8.5 m
Domain radius	20 m
Soil permeability	0.1 m^2/atm·s
Soil porosity	0.3
Soil density	1.7 g/cm^3
Adsorption isotherm parameter K_H	0.01
Steam flow rate	5 kg/h
Contaminant concentration	100 mg/kg of soil
Radius of contaminated zone	8 m
Depth of contaminated zone	3 m

[a] Unless otherwise stated in the captions, these parameters were used in making the runs plotted in Figs. 10–16.

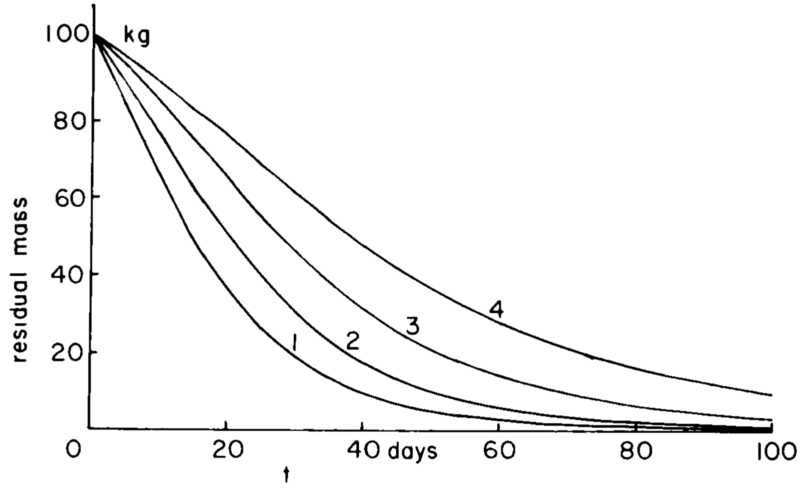

FIG. 12. The effect on contaminant removal of the extent to which the contaminant has spread laterally and vertically in the soil before steam stripping is started. The zones of contamination are (1) 16 m × 3 m, (2) 20 m × 4 m, (3) 24 m × 5 m, and (4) 28 × 6 m in diameter and depth, respectively. Other parameters are as in Table 1.

Figure 13 compares results of runs with permeabilities of 0.1 and 0.001 $m^2/atm \cdot s$; other parameters are as in Table 1. Soil gas pressures 1.0 m from the source are 1.007 and 1.546 atm, respectively. The percent discrepancy between the residual contaminant masses for the two runs is plotted versus time; this figure never exceeds 5%, from which we conclude that it is unlikely that neglecting the compressibility of the gas will introduce serious errors, given the experimental uncertainties in the parameters.

Figures 14, 15, and 16 compare results obtained with Lord's model and with ours. In Fig. 14 the bottom of the vadose zone is at a depth of 10 m and the steam is injected at a depth of 9.5 m. The presence of the vadose zone a short distance below the injection point results in quite marked differences between the results of the two models, with Lord's model predicting a very substantially slower rate of cleanup. Conditions for the runs shown in Fig. 15 are identical to those for the runs in Fig. 14, except that the steam is injected at a depth of 8.5 m. The same is true for Fig. 16, except that the steam is injected at a depth of 4.5 m. We conclude that the simple image potential approximation causes Lord's model to overpredict cleanup times, but that the error is not serious unless the steam is being injected fairly near the bottom of the vadose zone.

In this local equilibrium, linear isotherm model, cleanup times are inversely proportional to the linear isotherm parameter K_H. They are ap-

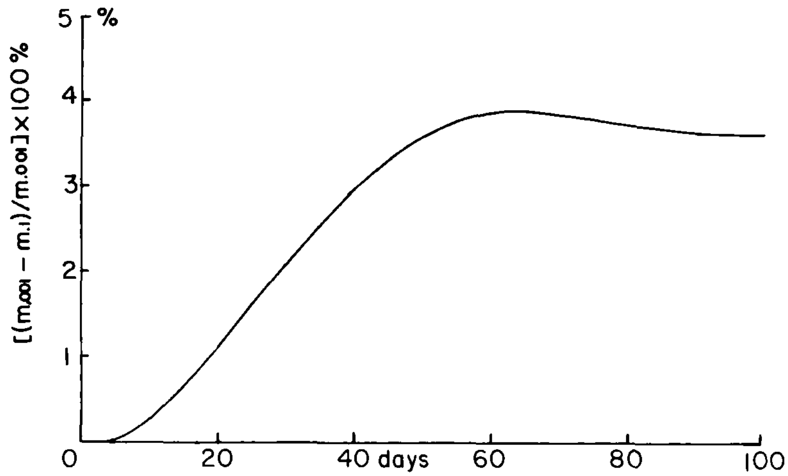

FIG. 13. The effect of soil permeability (or steam pressure) on contaminant removal. The permeabilities are 0.1 and 0.001 m^2/atm·s, with soil gas pressures 1.0 m from the steam source of 1.007 and 1.546 atm, respectively. The percent difference between the masses of residual VOC for the two runs is plotted versus time.

proximately inversely proportional to the rate of steam injection (kg/h), and, because of the use of this variable, are very weakly dependent upon the pneumatic permeability of the soil. In actual fact, the rate of steam injection itself will usually be controlled by the soil permeability, as well as by the radius of the gravel packing around the point of steam injection;

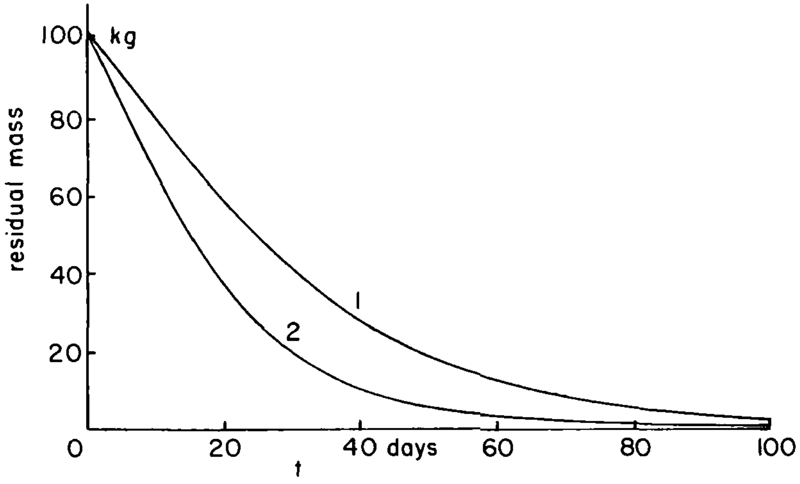

FIG. 14. Plots of residual contaminant mass versus time for Lord's image potential (1) and ours (2). Parameters as in Table 1, except that the steam is injected at a depth of 9.5 m.

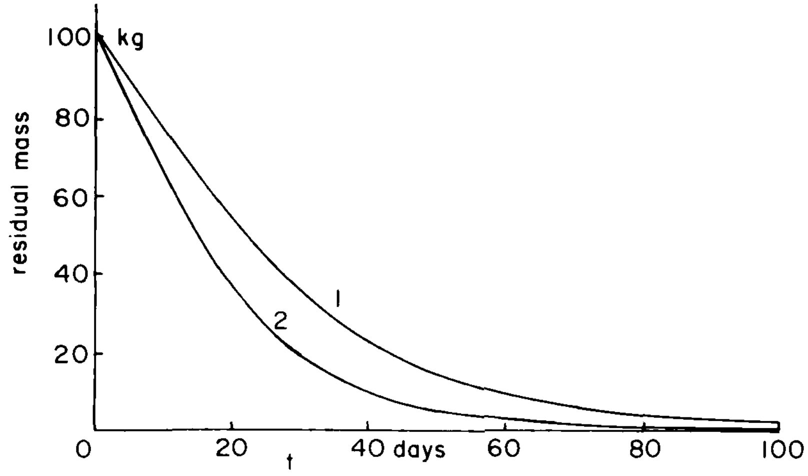

FIG. 15. Plots of residual contaminant mass versus time for Lord's image potential (1) and ours (2). Parameters as in Table 1. The steam is injected at a depth of 8.5 m.

at constant steam pressure, Q (the rate of steam injection) will be essentially proportional to both the soil permeability and the radius of the gravel packing. As a general rule, one would not use a well which is screened over a substantial portion of its length, since this would only lead to increased rates of cleanup of the overlying soil in the immediate vicinity of

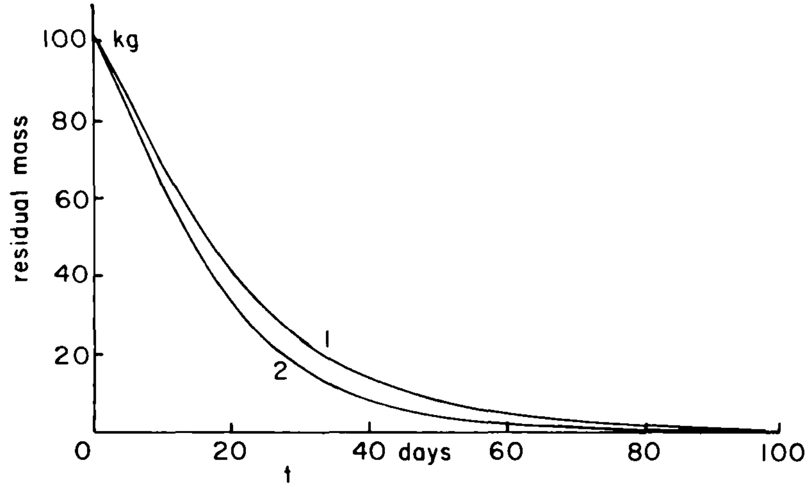

FIG. 16. Plots of residual contaminant mass versus time for Lord's image potential (1) and ours (2). Parameters as in Table 1, except that the steam is injected at a depth of 4.5 m.

the well, which will be rapidly cleaned up in any case. This increased rate of cleanup in the near vicinity of the well is purchased at the price of a very substantial decrease in the already relatively slow rate of cleanup of the more outlying regions in the domain of influence of the well.

The model for steam stripping presented here is certainly not to be regarded as definitive and final, inasmuch as it leaves a number of factors not addressed. It does not deal with the startup conditions during which the soil is being heated by the condensation of the steam and during which the soil moisture content (and therefore the pneumatic permeability) may be changing very substantially. We note, however, that the temperatures during the startup conditions are increasing to their steady-state values. Since the vapor pressures of the semivolatiles which are being stripped are very strongly increasing functions of the temperature, there is not likely to be much movement of these compounds until the temperature has reached or nearly reached its steady-state value. We therefore expect that Lord's (and our) neglect of startup transients probably does not introduce any major errors.

The assumption that the soil in the domain of interest has an isotropic, spatially constant pneumatic permeability is an approximation which may not be valid, requiring the use of numerical relaxation techniques to solve the analog to Laplace's equation, $\nabla k(x,y,z)\nabla p^2$, which is applicable under these conditions. The assumption of a linear adsorption isotherm for the contaminant in the soil could certainly be improved upon as supporting experimental data become available. One can expect the assumption of local equilibrium to be confounded in some (perhaps many) cases by rate-limiting kinetics of diffusion from the interiors of porous lumps of material of low permeability embedded in the domain of interest and by the kinetics of desorption of adsorbed contaminant. And, since some of the contaminants targeted by steam stripping are complex mixtures such as diesel fuel and other petroleum products, models for the steam stripping of such mixtures should be developed.

Our results suggest that two of the approximations in the model developed by Lord's group (use of a simplified image potential for generating the gas velocities and treating the gas as if it were incompressible) are unlikely to introduce serious errors into steam stripping calculations, especially when one considers the probable uncertainties in the experimental data from which the model parameters are assigned. If, however, the steam is being injected near the bottom of the vadose zone, errors could be of the order of 50%, and more complex calculations would then be warranted.

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