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ABSTRACT

A new method for evaluating the effectiveness of landfill liner systems has been developed that is based on contaminant transport. The current approach used by designers is to assume that leakage rate, or advective transport, is the only mode of mass transport through a composite liner. This is not necessarily true because diffusive mass transport occurs through defects and volatile organic compounds (VOCs) can diffuse through intact composite liners. The newly developed method accounts for advective and diffusive transport through intact and defective composite liner systems and does not involve the use of empirical equations for estimating leakage rates. The processes modeled include advection and diffusion through defects in composite liners and diffusion of VOCs through intact composite liners. This new method has been used to compare three alternative liner designs: (1) a U.S. Environmental Protection Agency (EPA) Subtitle D liner, (2) a State of Wisconsin Liner, and (3) a composite liner having a geosynthetic clay liner. The composite liner having a geosynthetic clay liner performed best in terms of leakage rate. However, composite liners having thicker soil liners performed better in terms of contaminant transport through the base of the liner system. The thicker composite liners had longer breakthrough times and less contaminant flux from the base. Results from this analysis can be linked to a hydrogeologic transport model and used to predict the impact of contaminant transport through the liner system on groundwater quality at some compliance point.

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INTRODUCTION

During the last decade, there has been increasing concern regarding the effects of unlined and leaking landfills on groundwater quality. The response to this concern in the United States has been development of Subtitle D of the Resource Conservation and Recovery Act (RCRA). Subtitle D requires that the minimum acceptable liner be 61 cm of compacted clay having a hydraulic conductivity no greater than 1 x 10^{-9} m/sec overlain by a geomembrane. A composite liner with a thicker layer of compacted clay (122 cm) is currently required in the State of Wisconsin.

Although Subtitle D requires that a composite liner be used, it also has a provision that permits an alternative liner design, provided that the alternative design is shown to be equivalent to the standard composite liner. Thus, designers are inclined to propose alternative liner designs that are less costly and/or use less air space than the liner specified under Subtitle D.

A key question is: What types of analyses must be performed to evaluate effectiveness and what is the definition of equivalency? The current approach is to assume that an alternative liner design is more effective if it discharges less liquid. However, this approach is too simplistic because the effectiveness of a liner depends not on leakage rate, but on the mass of contaminants discharged to groundwater. Although the mass discharged depends on leakage rate, it also depends on molecular diffusion and sorption on the lining materials. In some cases, molecular diffusion can dominate the flux of contaminants to groundwater (Shackelford, 1989). Thus, it is necessary to compare liners based on a contaminant transport perspective.

The objective of this study was to determine how effectiveness of landfill liners can be evaluated and to evaluate the effectiveness of several landfill liner designs currently being used in practice.

TRANSPORT MECHANISMS IN LINERS

The primary processes controlling contaminant transport through a landfill liner are the following: (1) advection of contaminants via seepage of liquid; (2) diffusion of contaminants in the presence of a concentration gradient; and (3) sorption on the lining materials (Rowe, 1987; Shackelford and Daniel, 1991a).

The advection-diffusion equation can be used to describe how these mechanisms govern the transport process (Javendel et al. 1984):

$$R\frac{\partial c}{\partial t} = -\frac{\partial(v_i c)}{\partial x_i} + \frac{\partial}{\partial x_i}(D_{ij}\frac{\partial c}{x_j}) \qquad (1)$$

where:

R is the retardation factor;

c is the concentration;
t is time;
v is the velocity of the fluid;
D is the diffusion coefficient;
x_i is the i^{th} orthogonal spatial coordinate; and
i and j are indices of the orthogonal coordinate axes.

Dispersion is not included because it is negligible at the low flow rates that exist in landfill liners (Shackelford, 1989).

Soil Liners

Hydraulic conductivity and effective porosity are the soil properties affecting advective transport through soil liners. Factors controlling the field-scale hydraulic conductivity and effective porosity of compacted clays have been studied extensively (e.g., Daniel, 1984; Elsbury et al., 1990; Liao and Daniel, 1989; Benson et al., 1994; Kim, 1996). Methods are now available to readily characterize field-scale hydraulic conductivity using *in situ* test methods (Daniel, 1989; Trautwein and Boutwell, 1994) or by evaluating construction quality control data (Johnson et al., 1990; Benson and Boutwell, 1992; Benson et al., 1994). Studies have also shown that the hydraulic conductivity and porosity of geosynthetic clay liners (GCLs) are readily characterized (Estornell and Daniel, 1992; Shan and Daniel, 1991; Lo et al., 1994).

Extensive research has also been conducted to describe diffusion in compacted clays and GCLs. It has been shown that the diffusion coefficient of contaminants in compacted clays and GCLs is less than that in free solution because diffusion in soil occurs through irregular pathways in pore space of the soil (Shackelford and Daniel, 1991a,b). The irregularity of the pathways may be quantified by the apparent tortuosity. To account for the effects that tortuosity has on the diffusion of chemicals, an effective diffusion coefficient is often used:

$$D* = D_o \tau_a \qquad \textbf{(2)}$$

where:

D^* is the effective diffusion coefficient;
D_0 is the free solution diffusion coefficient; and
τ_a is the apparent tortuosity.

Values of the free solution diffusion coefficient are readily available in the literature (e.g., Yaws, 1995). Values of the free solution diffusion coefficient typically range from 5 x 10^{-10} to 5 x 10^{-9} m^2/sec. A box plot of apparent tortuosities for different types of soils reported in the literature is shown in Figure 1. Apparent tortuosity may be back-calculated from results of column tests.

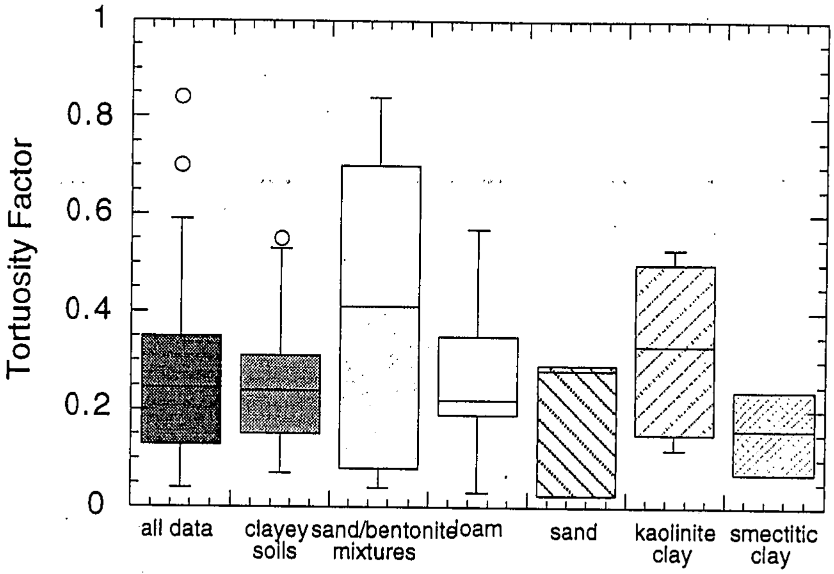

Figure 1. Tortuosity factors for several types of soils.

Effective diffusion coefficients for soils and contaminants may also be determined from results of column tests. There is a large existing database in the literature of diffusion coefficients for many organic and inorganic chemicals in different types of soils. A box plot of effective diffusion coefficients reported for several chemicals is shown in Figure 2. For inorganic and volatile organic compounds, D^* typically ranges from 1×10^{-11} m²/sec to 1×10^{-10} m²/sec (Shackelford, 1989; Kim, 1996).

Transport in compacted clay liners and GCLs is also affected by reactions that occur at the interface between the solid and liquid phases in soil (sorption), which are commonly described by the retardation factor R:

$$R = 1 + \frac{\rho_d K_d}{n} \qquad \textbf{(3)}$$

where:

ρ_d is the dry density;

K_d is the distribution coefficient (for a linear sorption isotherm and is frequently referred to as the partition coefficient); and

n is the total porosity.

The distribution coefficient is the ratio of mass sorbed per unit mass solid to the equilibrium concentration of the pore fluid. Distribution coefficients reported in the literature range from 3 to 96 mL/g (Foose, 1996). A summary of retardation factors for inorganic chemicals is shown in Figure 3.

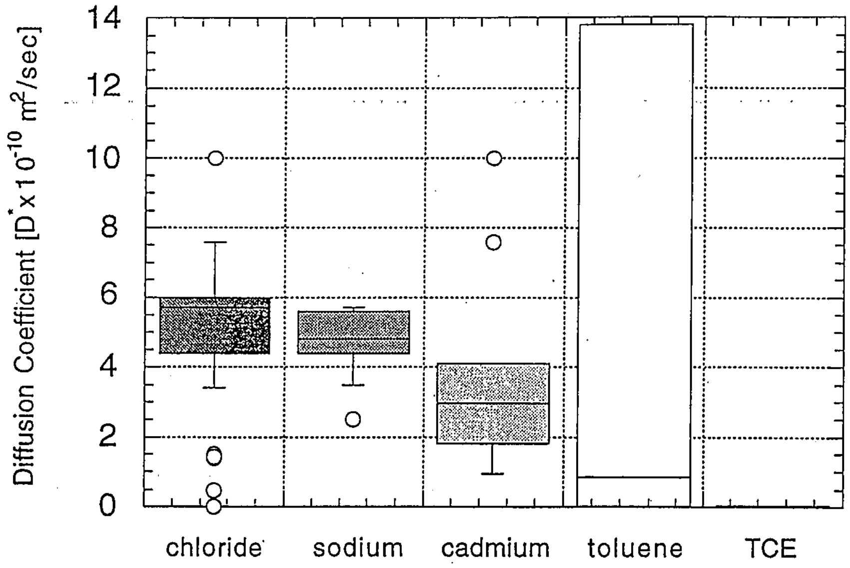

Figure 2. Diffusion coefficients for selected organic and inorganic chemical species.

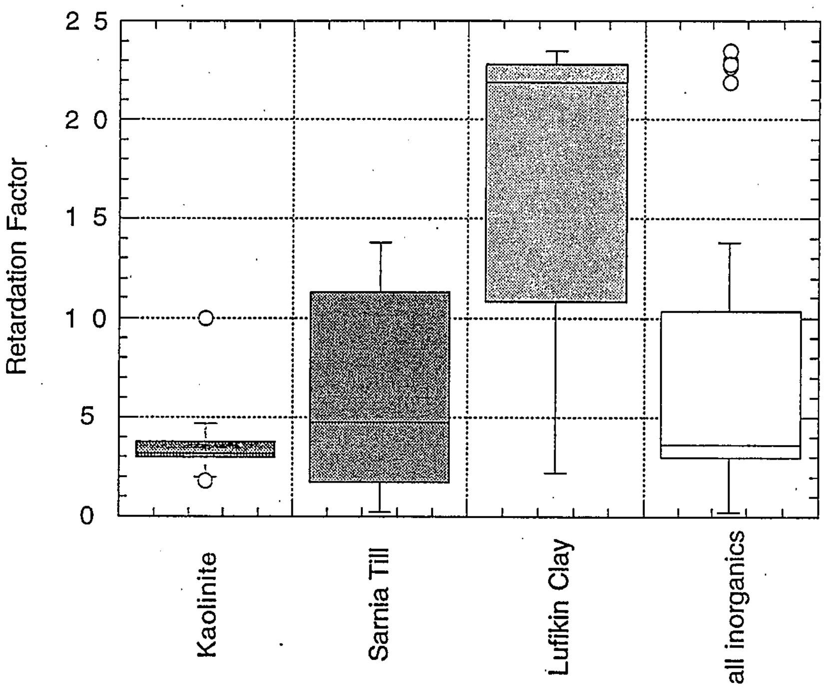

Figure 3. Summary of retardation factors for inorganics.

A summary of distribution coefficients for organic chemicals in soil is shown in Figure 4. It has been reported that the distribution coefficient for an organic in soil is related to the organic carbon fraction of the soil (Park et al., 1990). For organic chemical species and an assumed linear adsorption isotherm, the distribution coefficient may be estimated using the following relationship:

$$K_d = K_{oc} f_{oc} \tag{4}$$

where:

K_{oc} is the organic carbon-normalized soil sorption coefficient; and
f_{oc} is the organic carbon fraction of the soil (Park et al., 1990).

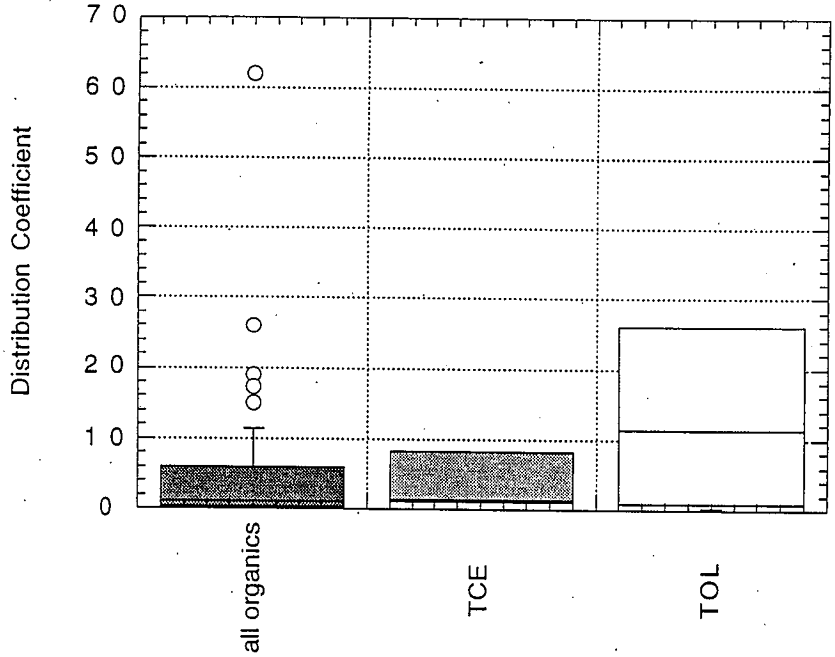

Figure 4. Summary of distribution coefficients for organic chemicals in soil.

From the results of an analysis of an extensive database of experimental work, Hasset et al. (1983) proposed the following relationships for hydrophobic compounds:

$$\log K_{oc} = 3.95 - 0.62(\log S) \tag{5}$$

where:

$$\log K_{oc} = 0.88 + 0.909(\log K_{ow}) \qquad (6)$$

S is the aqueous solubility; and
K_{ow} is the octanol-water partition coefficient.

Based on tests of 13 halogenated alkenes and benzenes on eight sediments, Schwarzenbach and Westall (1981) proposed the following relationship:

$$\log K_{oc} = 0.490 + 0.720(\log K_{ow}) \qquad (7)$$

Geomembrane Liners

Contaminant transport through geomembranes is different from that through soil liners. Advective transport occurs via flow through defects and diffusive transport occurs through interstitial spaces between polymer molecules in the intact material (Haxo, 1990). Equation 1 can still be used to describe this process by simulating the geomembrane as a thin impervious sheet (intact geomembrane) containing pervious heterogeneities (i.e., holes) (Figure 5).

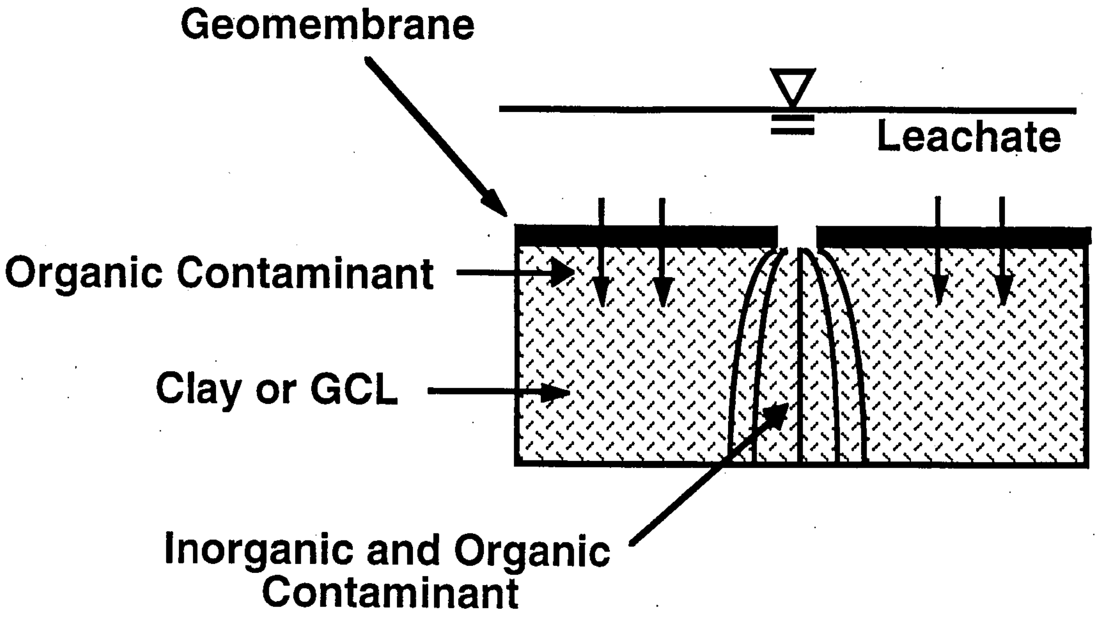

Figure 5. Transport in geomembrane liners.

Holes must be included in the analysis because nearly all geomembranes contain punctures, slits, and other defects from installation damage, inadequate seaming, and manufacturing flaws (Jaywickrama et al., 1988; Giroud and Bonaparte, 1989; Darilek et al., 1989). Recommendations regarding the number and size of holes to be used for design have been presented by Giroud and Bonaparte (1989) based on a synthesis of data from case studies. They recommend that designers account for one 3.1 mm^2 defect/4,000 m^2 to evaluate the performance of liner systems. Frequencies of defects as high as 370 holes/ha ranging in cross-sectional area from 0.5 to 78 mm^2 have been reported by Darilek et al. (1989).

Diffusive transport through geomembranes occurs in three steps: (1) partitioning of the chemical at the surface of the geomembrane exposed to the material being contained; (2) diffusion of the chemical through the geomembrane; and (3) partitioning of the chemical at the down gradient surface of the geomembrane (Figure 6) (Park and Nibras, 1993). Park and Nibras (1993) have demonstrated that organic chemical species can diffuse through geomembranes at appreciable rates. For example, Park and Nibras (1993) report results form laboratory tests and calculations indicating the breakthrough time of organic chemicals in 0.75 mm thick HDPE could be as short as 1 day and would reach steady-state flux within 1 week of permeation. In contrast, Haxo (1990) has shown that inorganic contaminants are not partitioned to the geomembrane and, hence, are not transported by diffusion.

The rate of transport of organics in HDPE is limited by the concentration of the contaminant that is partitioned at the upstream surface of the geomembrane (c_{gm}), which can be represented by the partition coefficient of the chemical for HDPE, $K_{d,gm}$ (Park and Nibras, 1993).

$$c_{gm} = K_{d,gm} c_o \qquad \textbf{(8)}$$

where:

c_o is the concentration of the chemical at the up gradient side of the geomembrane.

Organic chemicals typically exist in leachate in dilute aqueous solutions. A listing of reported distribution coefficients of chemicals for HDPE is shown in Table 1.

Diffusion through geomembranes is similar to diffusion in free solution with the exception that the diffusion coefficient is for diffusion through HDPE. Table 2 is a summary of diffusion coefficients for aqueous solutions of organic chemicals in HDPE. The reported diffusion coefficients range from 2.2 to 22.8 x 10^{-13} m^2/sec. With the exception of methyl chloride, diffusion coefficients for aqueous solution tested are on the order of 10^{-13} m^2/sec.

Composite Liners

Transport through composite liners can occur as the result of two processes: (1) advective transport through defects in the geomembrane, seams connecting the geomembranes, and through soil underlying the geomembrane, and (2) diffusion or permeation through an intact geomembrane or through soil underlying the geomembrane (Figure 5). Transport through composite liners may

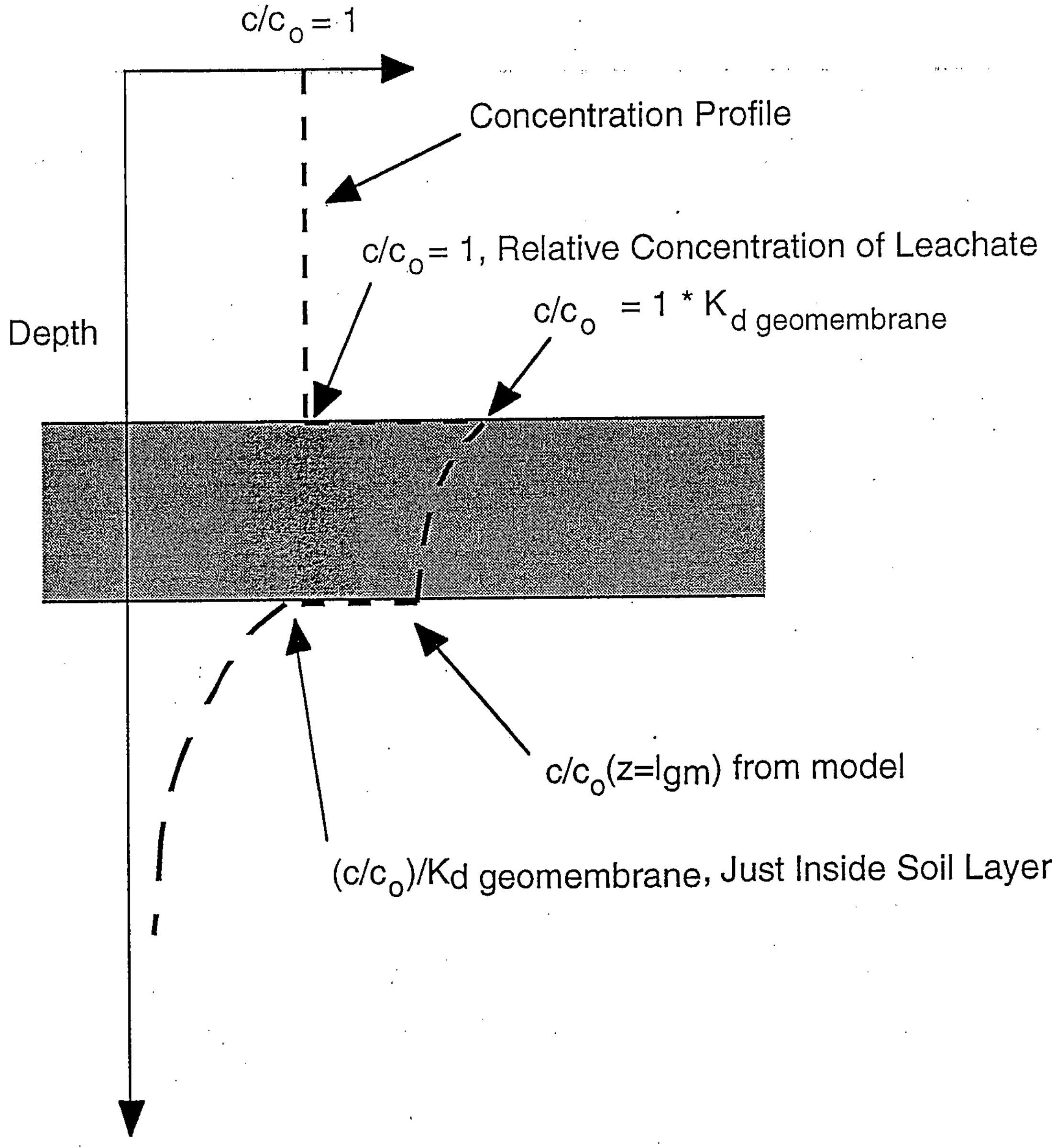

Figure 6. Illustration of transport process in an intact geomembrane.

Table 1. Partition coefficients of HDPE for organic chemicals at varying aqueous concentrations.

Chemical	Aqueous Concentration % of Solubility		K	Reference
	Initial	Final		
Toluene	100		140	Sakti, 1993
	100		148	Sakti, 1993
	100		150	Sakti, 1993
	100		137	Haxo and Lahey, 1988
	100		158	Haxo and Lahey, 1988
	90	73	63.45±14.90	Park and Nibras, 1993
	60	46	86.27±20.5	Park and Nibras, 1993
	50		145	Sakti, 1993
	30		83.92±2.76	Park and Nibras, 1992
	10		135	Sakti, 1993
	5	3.5	151.03±10.8	Park and Nibras, 1993
Trichloroethylene	100		113	Sakti, 1993
	100		115	Sakti, 1993
	100		114	Sakti, 1993
	100		131	Haxo and Lakey, 1988
	100		88	Haxo and Lahey, 1988
	100	83	52.25±0.10	Park and Nibras, 1993
	60	51.3	44.48±1.82	Park and Nibras, 1993
	50		113	Sakti, 1993
	30	25.1	53.79±2.29	Park and Nibras, 1993
	10		112	Sakti, 1993
	5	3.8	82.31±4.28	Park and Nibras, 1993
Methylene Chloride	100		6.3	Sakti, 1993
	100		6.2	Sakti, 1993
	100		6.4	Sakti, 1993
	90	89	2.36±0.053	Park and Nibras, 1993
	60	60	2.10±0.00	Park and Nibras, 1993
	50		6.5	Sakti, 1993
	45	45	1.68±0.056	Park and Nibras, 1993
	30	30	1.77±0.01	Park and Nibras, 1993
	10		6.3	Sakti, 1993
Xylene	100		455±2.85	Sakti, 1993
	100		450	Sakti, 1993

(continued)

Table 1. Continued.

Chemical	Aqueous Concentration % of Solubility		K	Reference
	Initial	Final		
	100		465	Sakti, 1993
	100		366	Haxo and Lahey, 1988
	100		322	Haxo and Lahey, 1988
	90	50	201.32±4.5	Park and Nibras, 1993
Toluene	60	34	192.63±0.57	Park and Nibras, 1993
	50			Sakti, 1993
	30	16	215.81±6.76	Park and Nibras, 1993
	10	5	310.22±6.00	Park and Nibras, 1993
	10		440	Sakti, 1993
O-Xylene	100		422	Haxo and Lakey, 1988
	100		352	Haxo and Lahey, 1988
P-Xylene	100		387	Haxo and Lahey, 1988
	100		390	Haxo and Lahey, 1988
Acetone	100		>0.0128	Haxo and Lahey, 1988
	100		<167	Haxo and Lahey, 1988
Benzene	100		54.3	Haxo and Lahey, 1988
	100		30	Haxo and Lahey, 1988
Methyl Ethyl Keytone	100		>0.0246	Haxo and Lahey, 1988
	100		<71	Haxo and Lahey, 1988
1,1,1-Trichlorethane	100		78.2	Haxo and Lahey, 1988
			112	Haxo and Lahey, 1988

Table 2. Diffusion coefficients for selected organic aqueous solutions.

Chemical	Initial Concentration (mmol/L)	Aqueous Concentration % of Solubility Initial	Final	$D_{eq} \times 10^{-9}$ (cm^2/sec)	Reference
Toluene				5.28	Sakti 1993
		100		4.33	Sakti 1993
		100		3.67	Sakti 1993
	5.03	90	73	5.14	Park and Nibras 1993
	3.35	60	46	4.72	Park and Nibras 1993
		50		3.56	Sakti 1993
	1.68	30	25	3.47	Park and Nibras 1993
		10		3.17	Sakti 1993
	0.28	5	3.5	5.55	Park and Nibras 1993
TCE		100		4.22	Sakti 1993
		100		5.22	Sakti 1993
		100		6.58	Sakti 1993
	8.37	100	83	7.55	Park and Nibras 1993
	5.02	60	51.3	7.22	Park and Nibras 1993
		50		4.69	Sakti 1993
	2.5	30	25.1	5.00	Park and Nibras 1993
		10		4.06	Sakti 1993
	0.42	5	3.8	4.44	Park and Nibras 1993
MC	234.4	90	89	22.8	Park and Nibras 1993
	157.5	60	60	15.8	Park and Nibras 1993
	117.1	45	45	19.7	Park and Nibras 1993
	78.75	30	30	44.7	Park and Nibras 1993
	13.12	5	5	5.83	Park and Nibras 1993
m-Xylene		100		3.59	Sakti 1993
		100		2.92	Sakti 1993
		100		2.6	Sakti 1993
	1.61	90	50	3.33	Park and Nibras 1993
	1.07	60	34	3.61	Park and Nibras 1993
		50		2.4	Sakti 1993
	0.54	30	16	3.06	Park and Nibras 1993
	0.19	10	5	3.10	Park and Nibras 1993
		10		2.19	Sakti 1993

be a combination of both processes. For example, leachate may flow through a defect in the geomembrane and then diffuse through the soil layer. Another example of transport through composite liners is the case in which the geomembrane is intact and organic chemicals diffuse through the geomembrane into the soil liner.

Little has been done to describe contaminant transport in composite liners. Studies that have been conducted have focused on the leakage rate through defects. Giroud and Bonaparte (1989) developed empirical equations for predicting flow rates in defective composite liners. For excellent contact between the geomembrane (as defined by Giroud and Bonaparte, 1989) and soil liner the following equation was proposed:

$$Q = 0.7a^{0.1}k_s^{0.88}h_w \qquad \textbf{(9)}$$

where:

Q is the leakage rate (m^3/sec);
a is the area of defect (m^2);
k_s is the hydraulic conductivity of the soil (m/sec); and
h_w is the head on the liner in meters.

For good contact, the leakage rate may be calculated using the following equation:

$$Q = 0.21a^{0.1}k_s^{0.74}h_w^{0.9} \qquad \textbf{(10)}$$

Studies by Giroud and Bonaparte (1989) and others (e.g., Jaywickrama et al., 1988; Bashel, 1993) provide insight into leakage rates that can be expected from composite liners. However, because these investigators have not dealt with contaminant transport, their models cannot be used by themselves to evaluate the effectiveness of composite liners.

PROCEDURES AND METHODS

APPROACH FOR NUMERICAL MODELING

Contaminant transport through composite landfill liners can be broken down into two problems: (1) advective and diffusive transport of inorganics and organics through defects in the geomembrane, and (2) diffusive transport of organics through non-defective composite liners. The only means of transport for an inorganic contaminant through a composite liner is through a defect in the geomembrane component of a composite liner. In contrast, an organic contaminant can be transported through a defect in the geomembrane and through the intact geomembrane.

To determine the total mass of contaminant discharged per unit area of liner, mass transport through defects in the geomembrane is added to mass transported through an intact composite liner (Eq. 11):

$$M_{total} = M_{defect} + M_{intact} \tag{11}$$

To use this approach, the two processes are assumed separable and additive. Mass transport through a single defect can be modeled using MODFLOW linked with MT3D (McDonald and Harbaugh, 1988; Zheng 1992). Mass transport through defects in a composite liner may be calculated by modeling mass transport through a single defect, and multiplying that by the number of defects per unit area (Eq. 12):

$$M_{defect} = M_{single\ defect} \left(\frac{number\ of\ defects}{area}\right) \tag{12}$$

provided the defects are spaced far enough apart such that they do not interact.

MODFLOW linked with MT3D is not a suitable tool for modeling mass transport through an intact composite liner. This is because MT3D cannot be used to simulate the process of organic contaminants partitioning into the geomembrane, then diffusing through the geomembrane, and finally partitioning from the geomembrane into the soil.

Mass transport through an intact composite liner can be modeled using a one-dimensional finite difference model. In the case of inorganic contaminants, no diffusion occurs through the geomembrane and hence the diffusive transport of an inorganic contaminant through the geomembrane is zero. The approach used in this study is illustrated schematically in Figure 7.

In this approach, the concentration profile near a defect is assumed to be unaffected by diffusion through the intact geomembrane. This is likely to be untrue. However, defects are relatively infrequent in composite liners and the assumption errs on the conservative side (it results in an over prediction of mass transport).

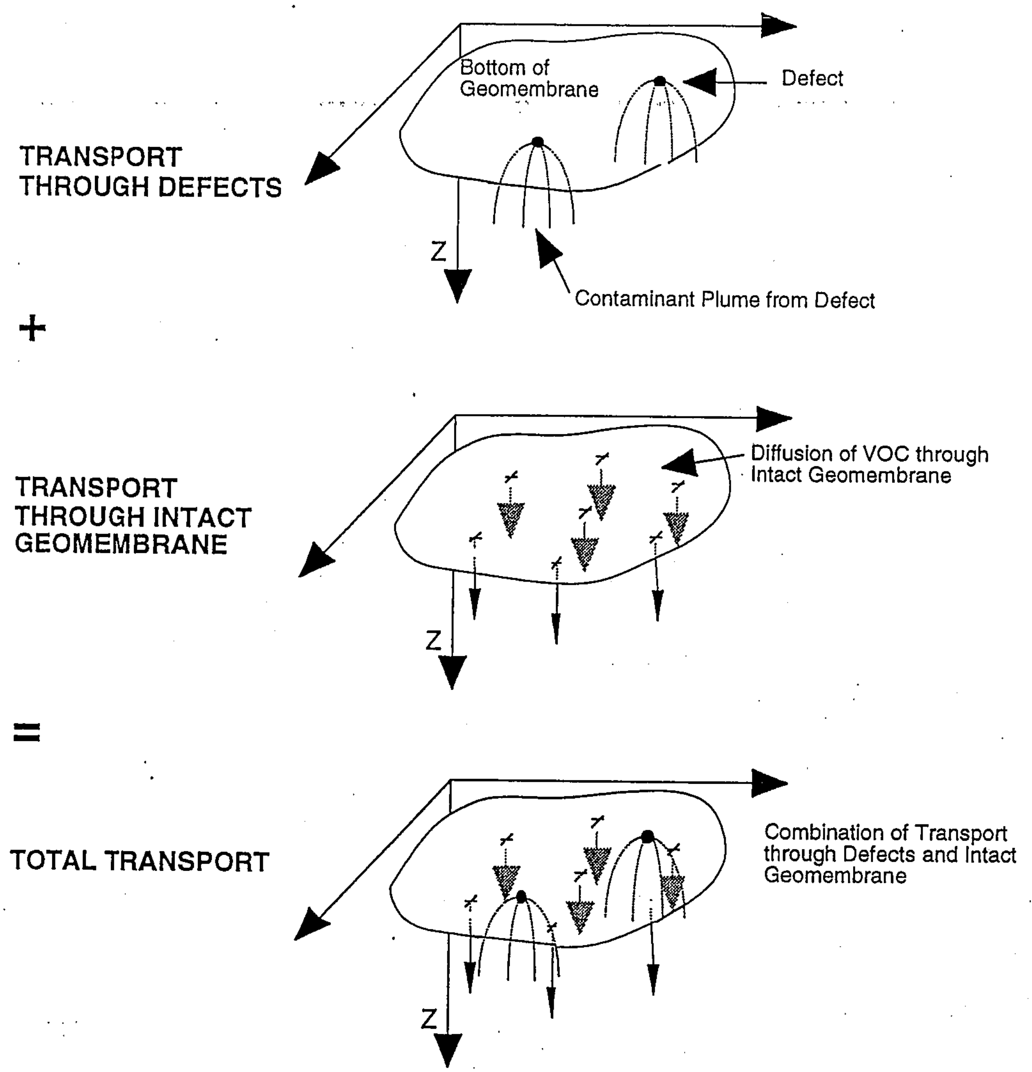

Figure 7. Schematic of approach used for modeling study.

Transport in Defective Composite Liners

Flow Solution

The head solution for flow through a defective composite liner is generated using MODFLOW. The governing equation solved by MODFLOW is:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) - R = S_s\frac{\partial h}{\partial t} \qquad \textbf{(13)}$$

where:

K_{xx}, K_{yy}, and K_{zz}, are hydraulic conductivities along the orthogonal spatial axes x, y, and z;
h is the total head;
R is a volumetric flux per unit volume from sources and/or sinks;
S_s is the specific storage; and
t is time.

This governing equation is subject to initial and boundary conditions which complete the mathematical expression of the flow system. MODFLOW solves these equations using the finite-difference method.

Simulating a Defective Composite Liner Using MODFLOW. Geomembranes having circular defects, rips, or faulty seams may be simulated using MODFLOW. If the soil liner is assumed to be homogeneous, leakage through a circular defect can be modeled as a radially symmetric problem. In this study one quadrant of the system is modeled. The area around a defect is modeled as a cube of soil with the axis of the defect lying on the edge of the cube (Figure 8). The algorithm used in MODFLOW is most suited for problems involving horizontal flow in aquifers. Thus, the liner system is modeled on its side.

A layer of no flow cells is used to simulate the geomembrane. Constant head cells are used to simulate a defect in the geomembrane. Because of the nature of finite-difference meshes, the defect is modeled using rectangular cells, and is approximated as a square having the same width as the radius of the circular defect being considered. The bottom boundary is modeled as a constant head layer. The soil liner is assumed to be saturated, homogeneous, and isotropic. Steady-state solutions to the system are developed using MODFLOW.

The parameters input into the model are spatial discretization in the x, y, and z directions, type of layer (confined or unconfined), and hydraulic conductivity of each cell. Input parameters for controlling the strongly implicit procedure (SIP) for solving the system are also required.

Boundary Conditions for Flow Model. Figure 8 is an illustration of a composite liner system modeled with a circular defect. The mathematical descriptions of the no flow boundaries on the lateral sides of the model are:

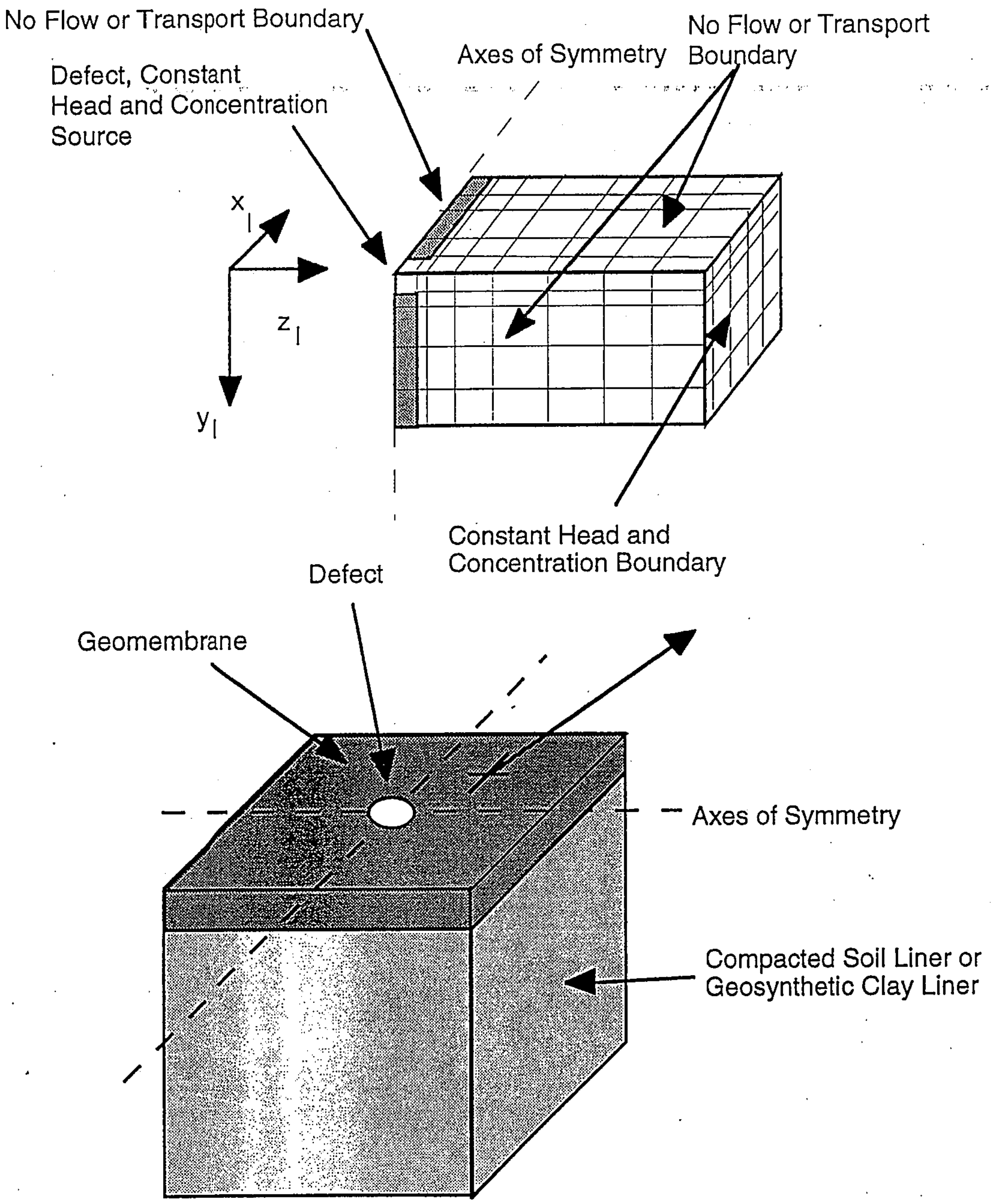

Figure 8. Conceptualization of composite liner having a circular defect.

$$\frac{\partial h}{\partial x}(x = 0,\ x = 1_x,\ 0 \leq y \leq 1_y,\ 0 \leq z \leq 1_z) = 0 \qquad \textbf{(14)}$$

$$\frac{\partial h}{\partial x}(0 \leq x \leq 1_x,\ y = 0,\ y = 1_y,\ 0 \leq z \leq 1_z) = 0 \qquad \textbf{(15)}$$

where:

$1_{x,y\,\mathrm{and}\,z}$ are the dimensions of the model in the x, y, and z directions (1_z is the thickness of the geomembrane plus the soil liner).

The no flow boundary for the geomembrane may be described as:

$$\frac{\partial h}{\partial z}\left(x \geq \frac{d_{hole}}{2},\ y \geq \frac{d_{hole}}{2},\ z = 1_{gm}\right) = 0 \qquad \textbf{(16)}$$

and a circular defect may be modeled as a constant head source:

$$h\left(0 \leq x \leq \frac{d_{hole}}{2},\ 0 \leq y < \frac{d_{hole}}{2},\ z = 0\right) = d_1 + 1_z \qquad \textbf{(17)}$$

where:

d_{hole} is the diameter of the defect; and
d_l is depth of leachate on the liner.

The bottom boundary condition is constant head:

$$h(0 \leq x \leq 1_x,\ 0 \leq y \leq 1_y,\ z = 1_z) = 0 \qquad \textbf{(18)}$$

Flow Model Verification. The flow model was tested to determine the validity of the model. The flow rate predicted was found to be independent of non-physical parameters (e.g., parameters controlling the solution of the governing equation) and a spatial discretization scheme was identified for which further reductions in grid-spacing did not result in changes in the flow rate predicted (Figure 9).

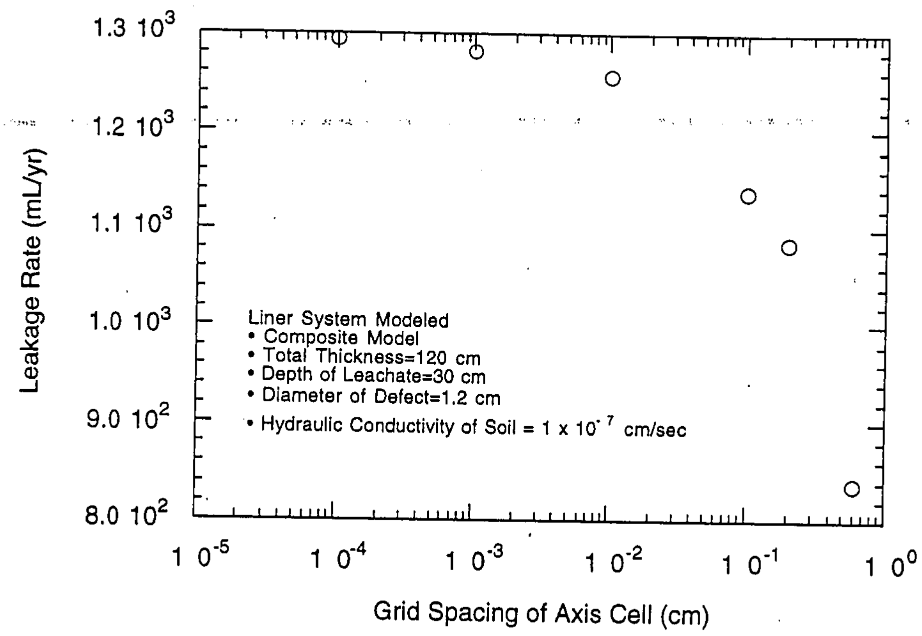

Figure 9. Leakage rate versus spatial discretization.

Contaminant Transport Solution

Contaminant transport through a defect in the geomembrane and then through the soil liner was modeled using MT3D. The governing equation solved by MT3D is the advection-diffusion equation:

$$R \frac{\partial c}{\partial t} = - \frac{\partial (V_i c)}{\partial x_i} + \frac{\partial}{\partial x_i}\left(D_{ij}^* \frac{\partial c}{\partial x_j}\right) - \lambda\left(c + \frac{\rho}{n} \bar{c}\right) \qquad \textbf{(19)}$$

where:

c is the concentration of a contaminant at point x and time t;
V is the pore fluid velocity calculated using the head solution generated using MODFLOW;
D^* is the effective dispersion coefficient;
R is the retardation factor, i is the ith orthogonal spatial coordinate;
i, j, and k are indices of the orthogonal coordinate axes;
t is time;
λ is the rate constant of the first-order rate reaction;
ρ is the bulk density of the porous medium;
n is the total porosity; and
$\bar{c}$ is the concentration of contaminants sorbed on the porous medium.

Retardation is assumed to be equilibrium-controlled linear or non-linear sorption:

$$R = 1 + \frac{\rho \partial \bar{c}}{n \partial c} \tag{20}$$

where:

$\frac{\partial \bar{c}}{\partial c}$ is defined by a distribution coefficient K_d.

Equation 24 is subject to initial and boundary conditions which complete the mathematical expression for contaminant transport in the liner system and is solved by MT3D using the finite-difference method.

Simulating a Defective Composite Liner using MT3D. Both the geomembrane and soil liner components of a composite liner are modeled using MT3D. The no flow boundaries are changed to no flux boundaries and the constant head source is changed to a constant concentration source.

Parameters input into the transport model are the effective dispersion coefficient in soil for the contaminant considered, longitudinal and transverse dispersivity, parameters for characterizing sorption onto soil solids, and a first order decay constant. Input parameters for controlling the numerical solution are also required.

Boundary Conditions for Transport Model. Figure 8 is a conceptual model for a composite liner having a circular defect. The mathematical description of the no transport boundaries on the lateral sides of the system are:

$$\frac{\partial c}{\partial x}(x = 0,\ x = 1_x,\ 0 \le y \le 1_y,\ 0 \le z \le 1_z,\ 0 \le t \le t_{total}) = 0 \tag{21}$$

$$\frac{\partial c}{\partial y}(0 \le x \le 1_x,\ y = 0,\ y = 1_y,\ 0 \le z \le 1_z,\ 0 \le t \le t_{total}) = 0 \tag{22}$$

where:

t is time.

The no transport boundary for the geomembrane may be described as:

$$\frac{\partial c}{\partial z}(x \ge \frac{d_{hole}}{2},\ y \ge \frac{d_{hole}}{2},\ z = 1_{gm},\ 0 \le t \le t_{total}) = 0 \tag{23}$$

and a circular defect may be modeled as a constant concentration source having a relative concentration (c/c_o) equal to a unit concentration.

$$\frac{c}{c_0}(0 \le x < \frac{d_{hole}}{2},\ 0 \le y < \frac{d_{hole}}{2};\ z = 0,\ t = 0 \le t \le t_{total}) = 1 \tag{24}$$

The bottom boundary condition is a constant concentration and may be described by:

$$\frac{c}{c_0}(0 \le x \le 1_x,\ 0 \le y \le 1_y,\ z = 1_z,\ 0 \le t \le t_{total}) = 0 \tag{25}$$

By varying the thickness of the liner (l_z), it is possible to simulate a zero-flux bottom boundary by locating the boundary sufficiently far away from the contaminant source.

Contaminant Transport in Non-Defective Composite Liners

Mass transport of organics in an intact composite liner can be modeled using a one-dimensional finite difference model. In the case of inorganic contaminants, no diffusion occurs through the geomembrane. Hence, diffusive transport of inorganic contaminants through geomembranes is zero. Using a one-dimensional model, the mass transport of organics through an intact composite liner can be calculated on a per unit area basis.

The governing equation for the one-dimensional diffusion model is:

$$\frac{\partial c}{\partial t} = D_{gm}\frac{\partial^2 c}{\partial z^2} - \lambda\, c_{gm} \qquad for\ (0 \le z \le 1_{gm}) \tag{26}$$

$$R\frac{\partial c}{\partial t} = D^* \frac{\partial^2 c}{\partial z^2} - \lambda\,(c + \frac{\rho}{n}\bar{c}) \qquad for\ (1_{gm} \le z \le 1_z) \tag{27}$$

where:

the z axis is aligned vertically;

D_{gm} is the diffusion coefficient of the contaminant through the geomembrane;
c_{gm} is the concentration of the solute in the geomembrane; and
the other variables are the same as those specified for the three-dimensional model.

This equation is subject to initial and boundary conditions which define the problem domain and is solved using the finite difference technique.

Development of One-Dimensional Finite-Difference Model

Geomembrane Formulation. As described previously, transport of organic contaminants in geomembranes is a three-step process: (1) the contaminant partitions into the geomembrane; (2) then diffuses through the geomembrane; and finally (3) partitions out of the geomembrane into the pore water in the soil beneath the geomembrane (Figure 6).

The inlet boundary is a constant source concentration:

$$c(z = 0,\ 0 \le t \le \infty) = (c_o)K_{d,gm} \tag{28}$$

where:

c_o is a unit concentration; and
$K_{d,gm}$ is the partition coefficient for the geomembrane and contaminant of interest.

This boundary condition characterizes partitioning of the contaminant from the leachate into the geomembrane. However, in the model, it is convenient to use the concentration of the solute normalized with respect to the partition coefficient because of the formulation of the boundary condition at the interface of the geomembrane and underlying layer.

In the one-dimensional model, the normalized concentration and node spacing is used. The grid spacing (Δz_m) and concentration is normalized using the partition coefficient:

$$\Delta z_m = \frac{\Delta z_a}{K_{d,gm}} \tag{29}$$

$$c_m = \frac{c_{gm}}{K_{d,gm}} \tag{30}$$

where:

Δz_m is grid spacing used in computation;
Δz_a is the actual grid spacing desired;
c_m is the concentration used in computation; and
c_{gm} is the actual concentration in the geomembrane.

Because the normalized concentration is used, the governing equation for the geomembrane must be modified to reflect this change in time and space:

$$\frac{\partial c}{\partial t} = \frac{D_{gm}\partial^2 c_{gm}}{K^2 \partial z^2} - \lambda c_{gm} \qquad for\ (0 \leq z \leq 1_{gm}) \tag{31}$$

The Crank-Nicholson equation for the interior nodes of the geomembrane is:

$$c_{k-1}^{n+1} + \frac{2(1 + s)}{s} c_k^{n+1} - s\ c_{k+1}^{n+1} = c_{k-1}^{n} + \frac{2(1 - s)}{s} c_k^{n} + s\ c_{k+1}^{n} \tag{32}$$

where s is:

$$s = \frac{D_{gm} \Delta t}{(\Delta z_m)^2} \tag{33}$$

Interface Formulation. Consider the i^th^ node at the interface and that the v^th^ layer is the geomembrane and the w^th^ layer is soil liner. A mathematical description of the continuity of flux across this boundary is:

$$D_v \left(\frac{\partial c_m}{\partial z_m}\right)_v = D_w^* \left(\frac{\partial c}{\partial z}\right)_w n_w \tag{34}$$

The central difference that can be used to describe the continuity of flux across this boundary is:

$$D_v \left(\frac{c_{modeled\ k+1} - c_{k-1}}{2\Delta z_{modeled}}\right)_v = D_w \left(\frac{c_{k+1} - c_{k-1}}{2\Delta z}\right)_w n_w \tag{35}$$

The Crank-Nicholson equation at the interface between the geomembrane and soil liner for the v^th^ and w^th^ layer is:

$$-c_{m\ k-1}^{n+1} + \varphi^{n+1} c_k^{n+1} - \gamma c_{k+1}^{n+1} = c_{m\ k-1}^{n} + \varphi^{n} c_k^{n} - \gamma c_{k+1}^{n} \tag{36}$$

where:

$$\gamma = \frac{c_w \Delta z_v}{c_{mv} \Delta z_w} n_w \tag{37}$$

$$\varphi^{n+1} = \frac{\beta_v^{n+1} + \gamma\beta_w^{n+1}}{2} \tag{38}$$

$$\varphi^{n} = \frac{\beta_v^{n} + \gamma\beta_w^{n}}{2} \tag{39}$$

and:

$$\beta_v^{n+1} = \frac{2(1 + s_v)}{s_v} \tag{40}$$

$$\beta_w^{n+1} = \frac{2(1 + s_w)}{s_w} \tag{41}$$

$$\beta_w^{n} = \frac{2(1 + s_v)}{s_v} \tag{42}$$

$$\beta_w^{n} = \frac{2(1 + s_w)}{s_w} \tag{43}$$

and s is the stability number:

$$s_v = \frac{D_{gm}\Delta t}{(\Delta z_m)^2} \tag{44}$$

$$s_w = \frac{D^* \ \Delta t}{R(\Delta z)^2} \tag{45}$$

Spatial discretization is selected based on using the same time step (Δt) for all layers and adjusting the thickness of the sub-layers of each layer (the normalized sub-layer thickness of the geomembrane) such that the solution is numerically stable.

Soil Liner Formulation. A mesh centered Crank-Nicholson finite difference scheme is used for transport in the soil liner. The Crank-Nicholson equation applied at all interior nodes of the soil liner is:

$$c_{k-1}^{n+1} + \frac{2(1 + s)}{s} c_k^{n+1} - s c_{k+1}^{n+1} = c_{k-1}^{n} + \frac{2(1 - s)}{s} c_k^{n} + s c_{k+1}^{n} \tag{46}$$

where:

n is the temporal index;
k is the spatial index in the vertical direction; and
s is the stability number defined by:

$$s = \frac{D^* \ \Delta t}{R(\Delta z)^2} \tag{47}$$

where:

D^* is the effective diffusion coefficient;
Δt is the length of the time step;
R is the retardation factor; and
Δz is the distance between nodes.

The retardation factor, R, is calculated from the linear sorption isotherm parameters for the soil liner and the solute and is assumed to be equilibrium-controlled linear sorption:

$$R = + \frac{\rho \partial \bar{c}}{n \partial c} \tag{48}$$

where $\partial c / \partial c$ is defined by the distribution coefficient, $K_{d,soil}$.

Boundary Conditions for One-Dimensional Contaminant Transport Model

Figure 10 is an illustration of the system modeled. The initial conditions for the model are a relative concentration of 1 at the top of the model and zero concentration throughout the profile:

$$\frac{c}{c_o}(z = 0,\ t = 0) = c_o K_{d,gm} \tag{49}$$

$$\frac{c}{c_o}(0 \leq z \leq 1_z,\ t = 0) = 0 \tag{50}$$

Where:

the coordinate $z = 0$ is defined to be just at the top edge of the geomembrane.

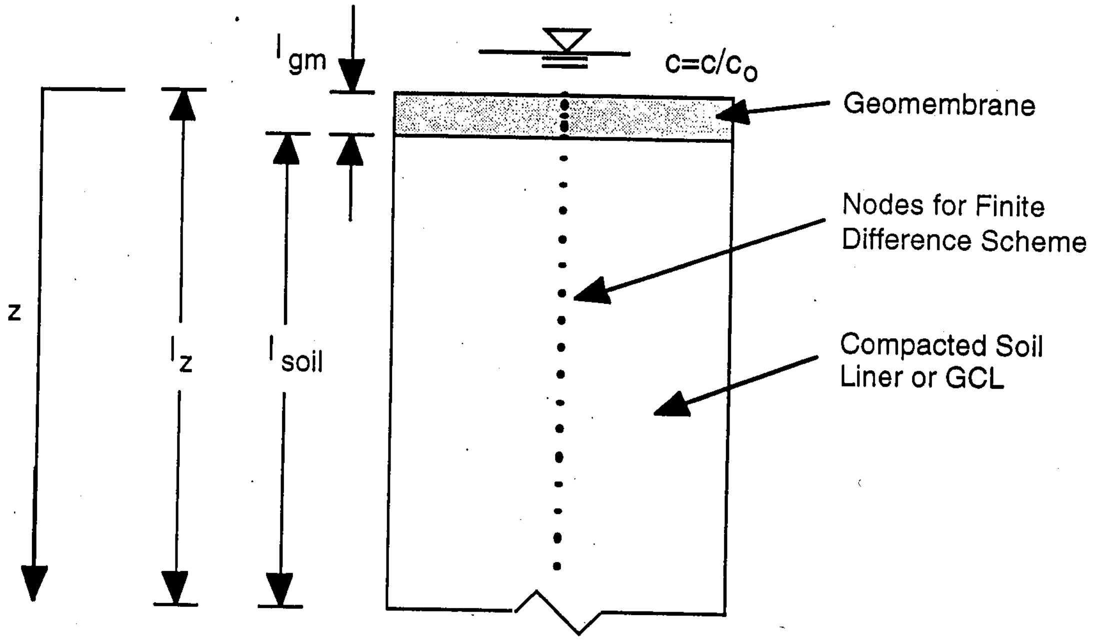

Figure 10. Finite-difference scheme for one-dimensional transport model.

The top of the model is considered to be a constant source concentration:

$$\frac{c}{c_o}(z = 0,\ 0 \le t \le \infty) = c_o K_{d,gm} \tag{51}$$

The bottom boundary condition is a constant concentration and may be described by:

$$\frac{c}{c_o}(z = l_z,\ 0 \le t \le t_{total}) = 0 \tag{52}$$

where:

t_{total} is the total length of the simulation.

By varying the thickness of the liner modeled (l_z), it is possible to simulate a zero-flux bottom boundary by locating the boundary sufficiently far away from the contaminant source. FORTRAN-77 was used for programming this scheme into a computer.

Validation of One-Dimensional Contaminant Transport Model. Results from the one-dimensional model may be compared to analytical solutions for limiting cases. The concentration profile for the case of a composite liner having an infinitely thick geomembrane is shown in Figure 11. Also shown is an analytical solution to this problem (Ogata and Banks, 1961). The comparison is favorable.

The analytical solution for a soil liner having the properties shown in Figure 11 is also shown along with the normalized concentration profile for the infinitely thick geomembrane. The concentration profile for a composite liner generated using the one-dimensional model lies between those for the infinitely thick soil layer and infinitely thick geomembrane. This is to be expected in that the diffusion coefficient in the geomembrane of the contaminant considered is an order of magnitude less than that in soil. Furthermore, because the geomembrane is a thin layer, the concentration profile for the composite liner is closer to that for the soil liner because the majority of the liner is composed of soil.

Simulations using the one-dimensional model were conducted and run to steady state. For this case, the results of the model approached that for the analytical solution for steady state diffusive transport through a composite liner:

$$D_{composite} = \frac{t_{gm} + t_{soil}}{\dfrac{t_{gm}}{K_{d,gm} D_{gm}} + \dfrac{t_{soil}}{D^{*}_{soil}\, n}} \tag{53}$$

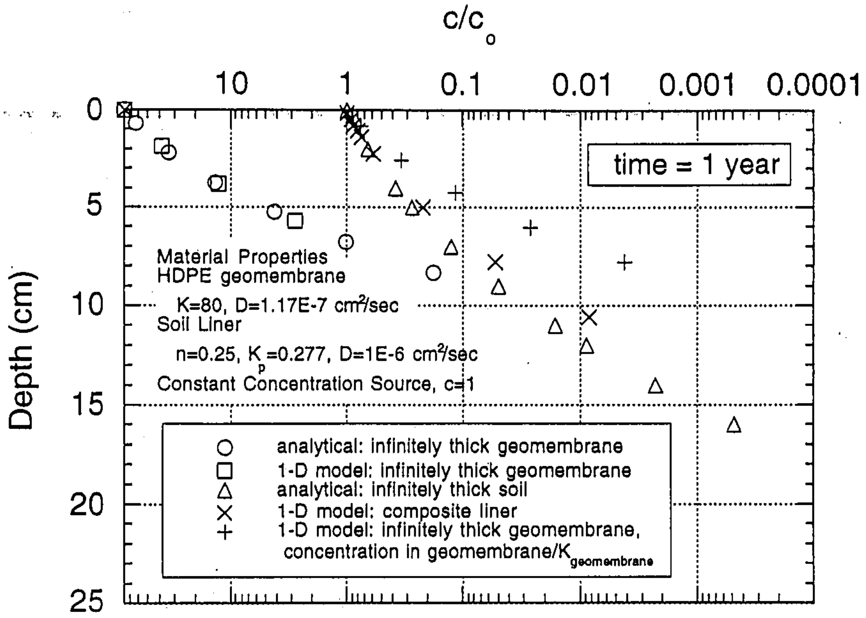

Figure 11. Verification of one-dimensional transport model.

This equation is the steady state diffusion coefficient for an organic contaminant that can partition into the geomembrane. Using Eq. 53 steady state mass fluxes through the base of a liner can be calculated using:

$$J_{d,\ composite} = \frac{\partial c}{\partial z} \cdot D_{composite} \tag{54}$$

where:

J_d is the steady state mass flux; and
$\partial c/\partial z$ is the concentration gradient.

The steady state composite liner diffusion coefficient can also be used in conjunction with the Ogata and Banks (1961) analytical solution for the advection-dispersion equation to calculate the steady state concentration at the base of the liner providing the boundary conditions are reasonably close to those required for the analytical solutions.

RESULTS AND DISCUSSION

LINER SYSTEMS EVALUATED

Three liner systems were studied to evaluate the effectiveness of each liner for minimizing contamination of the subsurface beneath a landfill. The three liner systems evaluated are shown in Figure 12 and are: (1) a USEPA Subtitle D liner; (2) a state of Wisconsin NR 500 composite liner; and (3) a composite liner have a geosynthetic clay liner. Composite liners having a geosynthetic clay liner are often proposed as an alternative to the Subtitle D and Wisconsin liners because they require less air-space in a landfill and are sometimes cheaper than constructing a compacted clay liner.

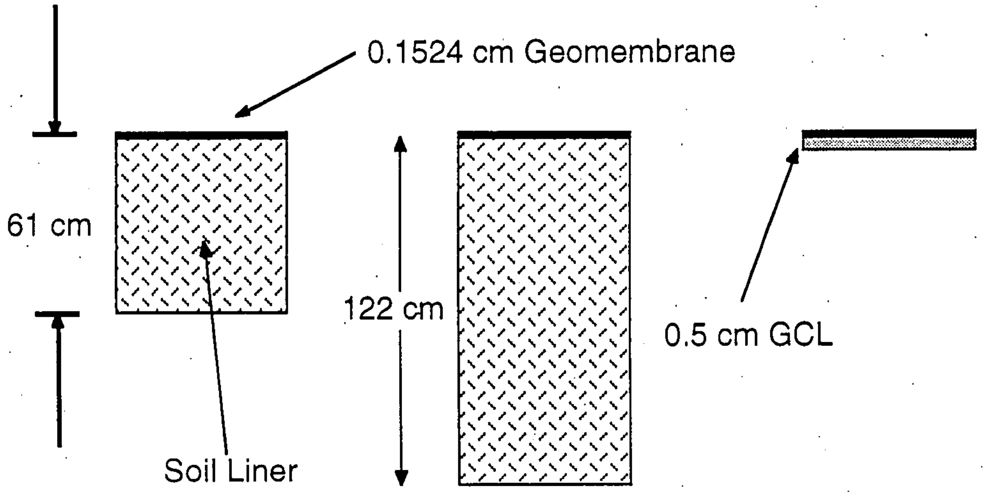

Figure 12. Illustration of the three liner systems modeled.

PROPERTIES OF THE LINERS ANALYZED

Properties of the liner systems analyzed were based on materials presented in the Introduction of this report and a database compiled by Foose (1996). The properties of the liners are listed in Table 3. The contaminant considered was toluene, an organic contaminant commonly found in leachate from municipal and hazardous solid waste.

The depth of leachate was assumed to be 30 cm. This is typically the regulatory specified maximum depth of leachate in a landfill. A typical 0.15 cm (60 mil) HDPE geomembrane was used and it was assumed that 2.5 defects/ha existed, each having a diameter of 1.2 cm. This is consistent with recommendations by Giroud and Bonaparte (1989). Values for partition coefficients, diffusion coefficients, and the first-order decay rate constant for toluene in the liner materials were taken from a database by Foose (1996) and Kim (1996). The source concentration modeled was 1 g/cm^3. It is important to note that the unit source concentration was selected so that the results from this investigation could be used for a variety of source concentrations.

Table 3. Properties of liner systems modeled.

Parameter	Value or Description
Type of contaminant	Organic (Toluene)
Depth of leachate	30 cm
Thickness of geomembrane	0.1524 cm (60 mil)
Diameter of defect	1.2 cm
Frequency of defects	2.5 defects/ha
Soil-geomembrane contact	Excellent
Partition coefficient of contaminant onto hope	147 mL/g
Diffusion coefficient of contaminant in geomembrane	5.55×10^{-9} cm^2/sec
Hydraulic conductivity of compacted clay liner	1×10^{-7} cm/sec
Hydraulic conductivity of geosynthetic clay liner	1×10^{-9} cm/sec
Effective diffusion coefficient of contaminant in compacted clay liner and geosynthetic clay liner	4.13×10^{-6} cm^2/sec (Toluene)
Longitudinal and transverse dispersivity of contaminant in soil	0
Partition coefficient of contaminant in compacted clay liner	1 ml/g (Toluene)
Partition coefficient of contaminant in geosynthetic clay liner	0.15 ml/g (Toluene)
First order degradation coefficient	1.27×10^{-7} 1/day
Bulk density of soil (and gcl)	1.77 g/cm^3
Length of simulations	50 Years
Boundary conditions for contaminant transport simulations	$c(z \geq 0; t = 0) = 0$ $c(z \leq 0; t > 0) = 1$ g/cm^3 $c(z =$ thickness of liner + 61 cm; $t > 0) = 0$

Results from Modeling

Results from the modeling consist of leakage rate, mass flux, and relative concentration at the base of the liner after a 50-year simulation. Based on these results, a comparison of the liner systems can be made.

Analysis of Defects in Composite Liners

A single defect was analyzed using the three-dimensional finite difference model described in the Procedures and Methods. Tables 4 and 5 are summaries of the results from this analysis. Leakage rates calculated for the three liners using the model range from 35.5 mL/ha/year for the composite liner having a GCL to 3,236 mL/ha/year for the Subtitle D liner.

Mass transport via defects in the Wisconsin liner was 19 orders of magnitude less than that through the liner having a GCL. For a source concentration of 50 mg/L, the mass transport via defects ranges from 1.44 x 10^{-19} μmg/ha/year for the Wisconsin liner to 3.36 μg/ha/year for the liner having a GCL.

Concentrations at the base of the liners beneath a defect are what would be expected based on the mass transport calculations. The concentration at the base of the liners after 50 years for a source concentration of 50 mg/L is 2.23 x 10^{-21} μg/mL for the Wisconsin liner compared to 47 μg/mL for the liner having a GCL.

Analysis of Intact Composite Liners

Intact composite liners were modeled using the one-dimensional model described in Procedures and Methods. Results from the analysis of intact composite liners are summarized in Tables 4 and 5. The relative concentrations at the base of the liners after 50 years are consistent with what would be expected based on the calculations of flux. The concentration at the base of the Wisconsin liner for a source concentration of 50 μg/L was 2.52 x 10^{-25} μg/L compared to 33.6 μg/L at the base of the liner having a geosynthetic clay liner.

The mass transport through an intact Wisconsin liner was 26 orders of magnitude less than that through the liner having a GCL. This relative comparison is consistent with that for the analysis of defective liners in that thicker liners yield less mass transport. The mass transport through an intact Wisconsin liner for a source concentration of 50 μg/L was 1.28 x 10^{-19} μg/ha/year compared to 1.69 x 10^{7} μg/ha/year for the liner having a GCL.

Total Mass Transport for Toluene in Composite Liners

The approach outlined in the Procedures and Methods was used to determine the total mass transport through 1 ha of the composite liners evaluated. The results are shown in Table 6. For a source concentration of 50 μg/L, the total mass flux ranged from 2.72 x 10^{-19} μg/ha/year for the Wisconsin liner to 1.69 x 10^{7} μg/ha/year for the liner having a GCL.

Table 4. Results from simulations for organic contaminant (based on source concentration of 1 g/mL).

Soil Component of Liner System	Leakage Rate (mL/ha/year)	Relative Concentration at the Base beneath Defects (g/mL, time = 50 years)	Mass Transport through Defects (g/ha/year = 50 years)	Relative Concentration at the Base beneath Intact Liner (g/mL, time = 50 years)	Mass Transport through Intact Liner (g/hr/year, time = 50 years)
Gcl	35.5	0.94	67.1	0.671	$3.37 X 10^{8}$
61 Cm Compacted Clay	3236	$5.71 X 10^{-13}$	$1.46 X 10^{-9}$	$7.38 X 10^{-14}$	$3.74 X 10^{-5}$
122 cm compacted clay	2323	$4.46 x 10^{-23}$	$1.41 x 10^{-19}$	$5.04 x 10^{-27}$	$2.56 x 10^{-18}$

Table 5. Results from simulations for organic contaminant (based on source concentration of 50 μg/mL).

Soil Component of Liner System	Relative Concentration at the Base beneath Defects (μg/ml, time = 50 years)	Mass Transport through Defects (μg/ha/year = 50 years)	Concentration at the Base beneath Intact Liner (μg/ml, time = 50 years)	Mass Transport through Intact Liner (μg/ha/year, time = 50 years)
GCL	47	3.36	33.6	$1.685 x 10^{7}$
61 cm compacted clay	$2.86 x 10^{-11}$	$7.28 x 10^{-11}$	$3.69 x 10^{-12}$	$1.87 x 10^{-6}$
122 cm compacted clay	$2.23 x 10^{-21}$	$7.05 x 10^{-21}$	$2.52 x 10^{-25}$	$1.28 x 10^{-19}$

Table 6. Total mass transport through liner systems analyzed.

Soil Component of Linear System	Total Mass Transport (g/ha/year) (C_o = 1 G/ml) (time = 50 years)	Total Mass Transport (μg/ha/year) (C_o = 50 μg/l) (time = 50 years)
GCL	3.37×10^{8}	1.69×10^{7}
61 cm compacted clay	3.74×10^{-5}	1.87×10^{-6}
122 cm compacted clay	5.45×10^{-18}	1.28×10^{-19}

Analysis of Results from Simulations

Based on results from modeling the three liner systems considered, a comparison of the liner systems can be made. If leakage rate is the performance criteria, the composite liner having a GCL performs best. The liner having a GCL had a leakage rate that was two orders of magnitude less than that for the Subtitle D liner and the Wisconsin liner (Tables 4 and 5). This is expected because the hydraulic conductivity of the GCL is two orders of magnitude less than that for a compacted soil liner. If it is considered that the gradient existing through the liner system and the soil underlying the liner systems is similar for the liner having a GCL and the liners having a compacted clay soil, it would be expected that the liner having the lower conductivity layer would have a lower leakage rate.

If mass transport of organic contaminants through the liner systems is used for comparison, the thicker liners perform better. This occurs for three reasons. First, the concentration gradient is greater in thinner liners. Second, the depth at which the flux is measured is shallower for thinner liners than that for the thicker liners. For the liner having a GCL, the depth at which the flux was calculated was 0.5 cm compared to 61 cm for the Subtitle D liner (Figure 12). This is the correct way to analyze the problem because usually when a GCL is used as an alternative liner, the elevation of the subgrade for the liner remains the same. Thus, the point at which the flux is calculated is at the same elevation for all three liner systems regardless of the liner system used. Third, the thicker soil liners have more sorptive capacity.

It is also important to note the contribution of defects to the total mass transport of an organic compound through a composite liner. For the composite liners having either a GCL or 61 cm of compacted clay, the mass transport through defects in composite liners is more than five orders of magnitude less than that through the intact composite liner. For inorganic contaminants, addition of a geomembrane to form a composite liner reduces the flux of contaminant from the liner system to that which is transported through the defect. However, organic contaminants, such as toluene, can diffuse through intact composite liners at appreciable rates. In fact, for composite liners having either a GCL or 61 cm compacted clay and few defects, the majority of the mass transport occurs through the intact liner system.

The results of the analysis on mass transport of toluene through defects can be extended to inorganic contaminants. The relative comparison between the liners should be the same even though the predicted mass transport is different. Typically, retardation factors for inorganic chemicals in bentonite GCLs are six times greater than that for typical liner soils (Foose, 1996). The Subtitle D liner and Wisconsin liner are 122 and 244 times thicker than the GCL liner, respectively. Hence, there is more sorptive capacity in the Subtitle D liner and Wisconsin than in a liner having a GCL and less inorganic contaminants will be transported through the thicker compacted soil liners. Foose et al. (1996) found from computer simulations that for inorganic contaminants and defective composite liners, thicker liners performed better in terms of reduced mass transport than thinner liners.

CRITIQUE OF TECHNIQUES FOR COMPARING LINER SYSTEMS

Current approaches used by designers to compare alternative liner designs are too simplistic because the effectiveness of a liner is judged primarily on leakage rate. The fundamental weakness in the analysis is the belief that the contaminant transport through a liner system is a function of leakage rate. This is partially true for inorganic contaminants. However, transport of inorganic contaminants through defects depends on diffusion as well as leakage rate (i.e., advection). In addition to transport through defects, organic contaminants can diffuse through intact composite liners at appreciable rates. Thus, mass transport of organic contaminants through intact composite liners is totally neglected in analyses that are based solely on leakage rates.

One common technique used for estimating contaminant transport to a compliance point is to use a water balance model (e.g., HELP) to estimate the leakage rate and then use a contaminant transport model to model transport of the contaminant from the base of the liner system to a compliance point. This makes it appear that the liner systems are indeed evaluated based on contaminant transport. The fundamental problem with this method is the assumption that the source concentration at the base of the liner depends solely on the leakage rate of the liner. Using this assumption, liner systems having lower leakage rates will always perform better, with respect to contaminant transport to some compliance point. In this section, it has been shown that concentrations at the base of the liner are also a function of the diffusive transport through the liner system, and thus, source concentrations based solely on leakage rate may be in error.

A valid evaluation of how well a liner sytem protects the groundwater must include the dominant mode of transport. Traditional methods based on leakage rate do not meet this criteria. For inorganic contaminants, an analysis of mass transport through defects should be performed. For organic contaminants, mass transport through the intact composite liner should be performed. Relative comparisons of liner systems based on transport of organics can be performed by estimating the steady-state diffusion coefficient for a composite liner and calculating the steady-state mass flux (Eqs. 53 and 54). Using this approach is conservative because decay and partitioning of the contaminant into the soil is ignored.

CONCLUSIONS

A new method for evaluating the effectiveness of composite landfill liner systems was developed. The method includes advective and diffusive transport of contaminants through defects in the geomembrane in addition to transport of volatile organic compounds though intact liner systems.

Three composite liner systems were evaluated in this study: an EPA Subtitle D liner; a State of Wisconsin NR 500 liner; and a composite liner having a GCL. The liner systems were compared based on mass transport of Toluene, a volatile organic compound commonly found in landfill leachate. The composite liner having a GCL had the lowest leakage rate of the three liners analyzed. However, if mass of contaminants through the bottom of the liner system was used as the performance criteria, the thicker liners performed better. In fact, the mass transport through the liner having a GCL was 13 orders of magnitude greater than that through the Subtitle D liner system. The difference between the liners having a GCL and those having a thicker compacted clay liner with respect to contaminant transport exists because: (1) the concentration gradient is greater in thinner liners than thicker liners; (2) the depth at which the mass flux is calculated is closer to the source in thinner liners; and (3) thicker soil liners have more sorptive capacity than thinner liners.

Leakage rate is not a good indicator of how a liner performs with respect to contaminant transport. Comparisons of liner systems must include the dominant mode of transport. For volatile organic compounds, the analysis should include diffusion through the intact composite liner. For inorganic contaminants, only mass transport through defects needs to be analyzed. Results of these analyses can then be used as the boundary condition for a hydrogeologic transport model to evaluate the impact of a landfill on the groundwater quality around a landfill site.

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