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WELDON SPRING SITE REMEDIAL ACTION PROJECT

Groundwater Operable Unit Feasibility Study

Technical Memorandum
Task No. 852
Simulation of Leachate Flow and Transport from the Disposal Cell Through the Vadose Zone

Technical Memorandum No. 3840TM-1009-00

July 1996

Rev. 0

Prepared by

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for

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St. Charles, Missouri 63304

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1.0 OVERVIEW

The Weldon Spring disposal cell site is underlain by about 30 feet of low-permeability silts and clays with hydraulic conductivities ranging from 10^{-09} cm/sec to 10^{-07} cm/sec (see Section 3.1). Depth to water is about 40 feet. The time required for leakage from the cell to reach the groundwater table could be many years.

Most of the leachate from the disposal cell will drain to a sump and be collected in the primary leachate collection system. Data on existing disposal systems indicate that the leachate flow rate will decline very rapidly after the cell is closed and will approach a steady-state condition within a few years. Leachate collected in the secondary leachate collection system will follow the same pattern, except that the flow rate will be much lower. It is unlikely that there would be a gross failure in the liner system during this early period when the leachate flow rates are the highest.

Leakage through the cell liners can be estimated by examining data from existing cells with similar construction. Materials used in the liner system are designed to perform for hundreds if not thousands of years. Most liner failures will be the result of damage during construction and improperly completed seams. Leakage can be estimated using various approximations developed based on empirical tests and theoretical derivations of flow through holes and other imperfections in the liner material. Estimated disposal cell leakage rates for a single liner are generally very small, on the order of 0.5 gallon per acre per day, even assuming 12 inches of leachate ponding above the liner. Leakage through the secondary liner would be even less.

The purpose of this report is to provide estimates of leachate flow rates through the vadose zone to the groundwater to support the development of a strategy for disposal cell compliance monitoring.

2.0 GEOLOGY

This technical memorandum addresses only the unconsolidated geologic materials, or overburden, that occur above the bedrock and generally above the water table and are located within the disposal cell footprint. The overburden consists of six layers or units of varying thickness and lateral extent that will separate the bottom of the disposal cell from the groundwater table. Beginning with the uppermost layer, these units are (1) topsoil/fill, (2) loess, (3) Ferrelview Formation, (4) clay till, (5) basal till, and (6) residuum. The following layer description was taken from Kleeschulte (1994) and Bognar (1991).

2.1 Topsoil/Fill

The topsoil/fill unit is made up of clayey silt and silty clay with varying organic content. The thickness of this unit within the Weldon Spring site ranges from 0 to 30 feet. This unit will be removed during cell construction and was not evaluated for this task.

2.2 Loess

The loess is a wind-deposited unit ranging in thickness from 0 to 11 feet, and is composed of 90% to 95% fine-grained material with a low to medium plasticity index. This unit will also be removed during cell construction.

2.3 Ferrelview Formation

This unit is present throughout the disposal cell area with an average thickness of 10 feet. The Ferrelview Formation is clay and silty clay with minor amounts of chert and rock fragments and some iron oxide nodules. This unit has a low to high plasticity index and a low average permeability of 2.34^{-08} cm/sec.

2.4 Clay Till

The clay till is similar to the Ferrelview Formation. The clay is very stiff, has a low to high plasticity index, and contains small chert fragments, iron oxide nodules, and igneous and metamorphic rocks of glacial descent. The thickness of clay till ranges from 2.3 feet to 30 feet within the disposal cell area, with an average thickness of 20 feet. The average permeability of the unit is about 2.29^{-08} cm/sec.

2.5 Basal Till

The basal till is composed of angular chert fragments, gravel, and cobbles of glacial origin in a matrix of semi-consolidated sand, silt, and clay. The thickness of the unit is very irregular and ranges from 0 to 11 feet.

2.6 Residuum

The residuum is derived from the physical and chemical weathering of the Warsaw and Burlington-Keokuk Limestone bedrock. This unit is very heterogeneous and ranges from gravelly clay to clayey gravel. The thickness ranges from 5 feet to 20 feet within the disposal cell area.

3.0 HYDROLOGIC PARAMETERS

3.1 Saturated Hydraulic Conductivity

Numerous tests have been performed to determine the hydraulic conductivity of the overburden soils. Using Boutwell's two-stage-borehole method (MKES 1993), hydraulic conductivity values for the Ferrelview Formation and the clay till were estimated to be 1.2×10^{-09} cm/sec and 3.25×10^{-09} cm/sec, respectively. Results of earlier testing (MKES 1994) suggest hydraulic conductivity values ranging from 1.3×10^{-08} cm/sec for the Ferrelview Formation to 6.9×10^{-09} cm/sec for the clay till. Average values obtained from triaxial permeability tests (MKES 1994) are 8.94×10^{-09} cm/sec for the Ferrelview Formation, 6.46×10^{-08}cm/sec for the clay till, 2.45×10^{-07} cm/sec for the basal till, and 2.58×10^{-07} cm/sec for the residuum. Bognar (1991) lists values of 8.34×10^{-08} cm/sec and 2.29×10^{-08} cm/sec for the Ferrelview Formation and the clay till, respectively. Other results using the Submersible Pressure Outflow Cell method (Constanz 1984) are reported as 6.5×10^{-07} cm/sec for the clay till and 5.2×10^{-07} cm/sec for the Ferrelview Formation.

3.2 Moisture Content

The in situ values of moisture content are near saturation (MKES 1993). This observation is consistent with the low permeability and fine particle size of the units. With the depth of the water table at about 40 feet, the capillary rise above the water would result in near saturated conditions, even without infiltration from precipitation. Only the coarser (and more permeable) residuum has a moisture content much below saturation. The average saturation for each unit is listed below:

• Ferrelview Formation	90% saturation
• Clay till	93%
• Basal till	91%
• Residuum	65%

3.3 Porosity

Because of the fine texture of the soils, the total porosity is relatively high (MKES 1993). Average total porosity is shown below:

• Ferrelview Formation	0.403
• Clay till	0.378
• Basal till	0.362
• Residuum	0.442

It is the effective porosity, however, that determines the hydraulic properties of the soils. Plastic clays exhibit a high porosity, but due to the nature of the clay particles, much of the pore space is not connected and does not contribute to the overall permeability of the system. The portion of the total porosity that contributes to the hydraulic capacity of the soil is referred to as the effective porosity. The effective porosity of clays is very low and is responsible for the low hydraulic conductivity observed. The results of the tests indicate effective porosity ranges from 5% to 11.7% (MKES 1993). These results are consistent with the soil-moisture-characteristic curve data.

3.4 Soil-Moisture-Characteristic Curve

The soil-moisture-characteristic curve describes the relationship between the suction head and the moisture content. It is used to develop a relationship between the unsaturated hydraulic conductivity and the moisture content or suction head. As the moisture content in a soil decreases, the unsaturated hydraulic conductivity decreases. The ratio of the unsaturated to the saturated hydraulic conductivity is called the relative hydraulic conductivity. The hydraulic conductivity of a dry soil can be many orders of magnitude lower than for the same saturated soil, even over the narrow range of moisture contents found at the Weldon Spring disposal cell site. The hydraulic conductivity curve is shown in Figure 1.

Capillary moisture tests were performed for soil samples from the Weldon Spring site. The Van Genuchten parameters for modeling the hydraulic conductivity/moisture content relationship were estimated (MKES 1993) using a method described by Van Genuchten (1978). These values were used in the computer model. The estimated parameters are listed below. The modeled soil moisture curve is shown in Figure 2.

- α 0.0000 - 0.0011 (used 0.0899 m^{-1})
- n 1.53 - 2.24 (used 1.952)
- θr 0.27 - 0.40 (used 0.352)
- θs 0.35 - 0.45 (used 0.402)

The very narrow range between the saturated and residual moisture content indicates the value of the effective porosity. It may be assumed the residual moisture content cannot be drained and, therefore, represents the nonconnected pore space. The difference between the saturated moisture content and residual moisture content is approximately the minimum value of the effective porosity. The resulting values, ranging from 0.04 to 0.17, are reasonable and close to the minimum value determined in the bromine ion tracer test (Maxim 1995).

3.5 Transport Parameters

No data on site-specific dispersion parameters were available for this modeling effort. Studies have been completed, however, to estimate distribution coefficients, k_d, for various constituents found at the site (Schumacher and Stollenwerk 1991). The results of laboratory batch experiments indicate that significant sorption of molybdenum (VI) and uranium (VI) occurs within the Ferrelview Formation and clay till. Sorption of molybdenum and uranium were controlled by pH, with complete removal of molybdenum from solutions at a pH less than 5.0. However, uranium could be relatively mobile within the overburden if solution pH values are near neutral and alkalinity values are large (Schumacher 1993).

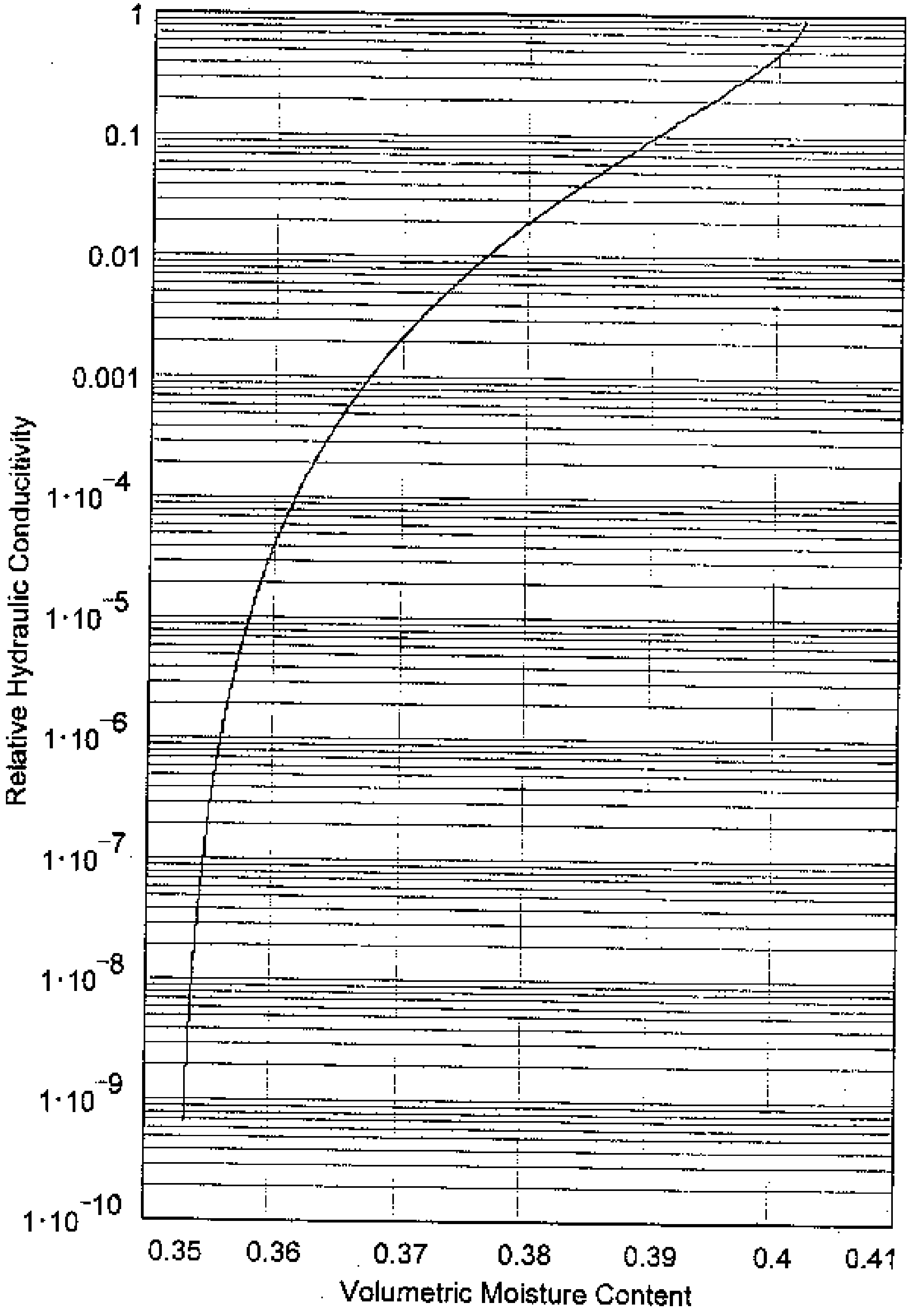

Figure 1 **Relative Hydraulic Conductivity versus Moisture Content**

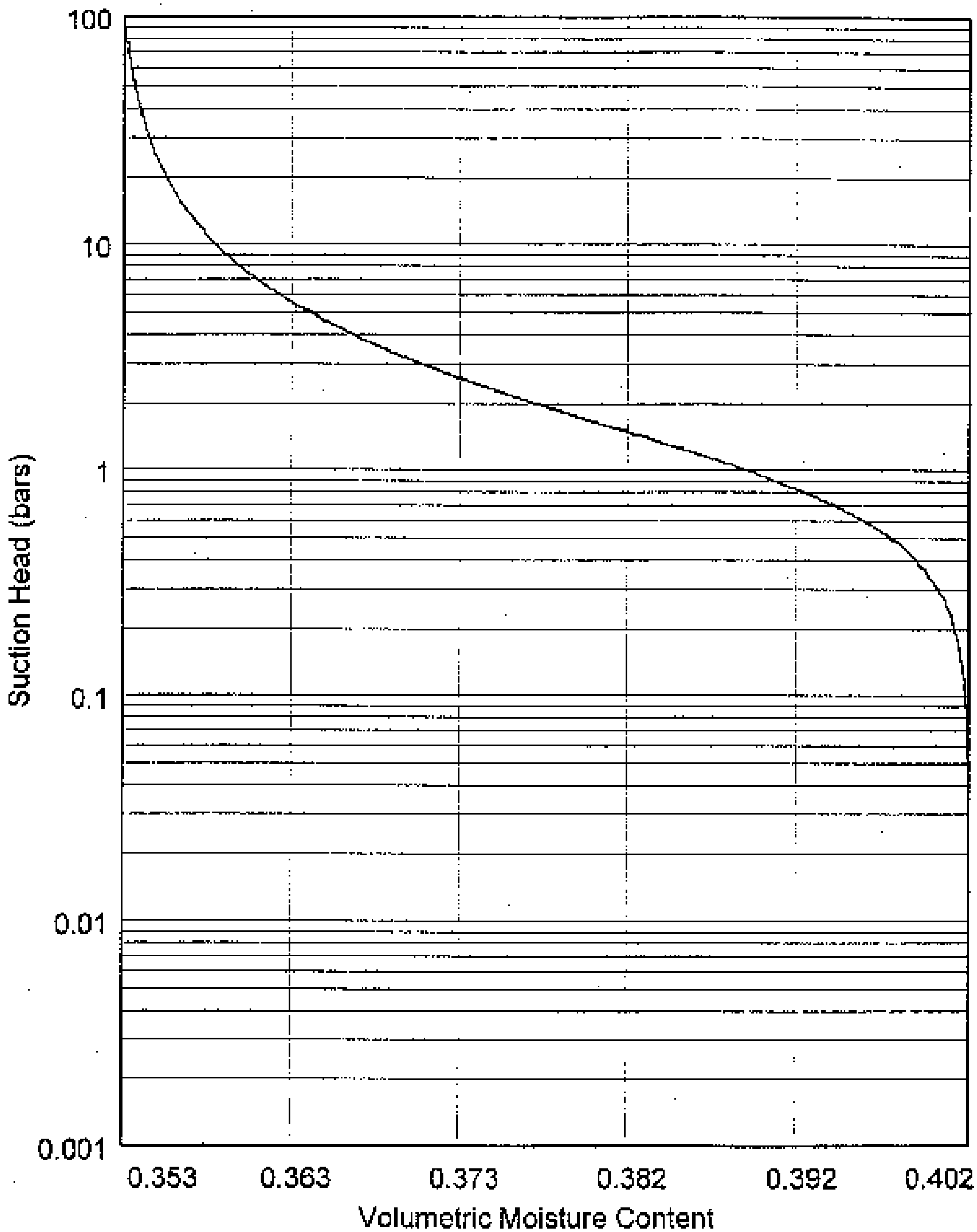

Figure 2 **Soil Moisture Characteristic Curve**

The k_d values for molybdenum and uranium ranged from 1 mL/gram to 430 mL/gram for molybdenum and from 10 mL/gram to 1,990 mL/gram for uranium. However, the distribution coefficient model applied was unable to accurately simulate the batch test results for molybdenum and uranium. Sorption was low (k_d less than 1) for calcium, magnesium, sodium, sulfate (SO_4), nitrate (NO_3), and strontium. Sorption was higher (k_d greater than 1) for fluorine, chromium, lead, lithium, and vanadium.

Adsorption can be measured as the concentration of solute mass in the solid phase. Adsorption can be estimated as a function of the solute concentration in the liquid phase. One such function is the linear Freundlich isotherm:

$$c_s = K_d \cdot c$$

where

c_s is the concentration of the solute mass in the solid phase, M/M (mass/mass);
k_d is the equilibrium distribution coefficient, L^3/M ($length^3$/mass); and
c is the solute concentration in the liquid phase, M/L^3 (mass/$length^3$)

The total concentration is equal to c_s times volume of soil times bulk density of the soil. The sorption process is assumed to occur instantly whenever there is an imbalance between the solid phase and the liquid phase, as implied by the function. Only when the equilibrium between the solid and the liquid phase and the adsorption capacity of the soil are reached is the solute mass free to be transported through the vadose zone in the liquid phase.

Adsorption is an important parameter for estimating chemical transport. The equation for the linear Freundlich isotherm shows that a large solute mass can be adsorbed relative to the concentration in the liquid phase. Using the Freundlich equation and a k_d of 1 mL/gram, the adsorption capacity of the vadose zone within a 2.2-meter-diameter soil cylinder, 10 meters deep, is approximately 243 kg when the solvent concentration is 1 gram/L and the bulk density is 1.6 gram/cm^3. The solute mass inflow is 1.89 gram/day for a leakage rate of 0.5 gal/day. Therefore, the soil immediately beneath a leak can adsorb 352 years (243 Kg/1.09 gram/day) of solute from the leakage, assuming there was no previous contamination.

The parameter dispersivity, which is a measure of the dispersive properties of a hydrogeologic system, has been known to be scale dependent (Fried 1975, Gillham *et al.* 1984, and Pickens and Grisak 1981a,b). Dispersivity depends on the mean travel distance of solute or the scale of the system, and there is trend for larger dispersivities to be asociated with larger contamination zones. The scale effect is significant for shorter travel distances, but decreases at larger travel distances and eventually approaches a constant value. Pickens and Grisak (1982a,b) developed a general dispersivity-travel distance relationship that requires site-specific experimental data for calibration. They also developed an empirical equation by averaging the proportionality constants from field studies by various investigators. Applying this empirical equation with a 5-meter mean travel distance (10-meter vadose zone thickness), the longitudinal dispersivity was estimated to be 0.5 meter.

4.0 DISPOSAL CELL LEAKAGE

4.1 Leachate Collection and Retention System

The disposal cell liner is composed of a primary and a secondary leachate collection system (MKES 1995a). The system will be constructed as described below (from the bottom up):

- 3-foot compacted clay liner
- Geosynthetic clay liner (GCL) with HDPE geomembrane on top
- Geonet for a secondary (redundant) leachate collection and removal system
- HDPE geomembrane
- 8-inch gravel drain layer with HDPE pipe collection system
- 8-inch sand filter layer

The cell liner is composed of separate, isolated, primary and secondary leachate collection and retention systems (LCRS). Most of the leachate from the waste will be drained from the primary LCRS. Under normal operating conditions, the secondary LCRS will be free of leachate, with the exception of leakage through holes in the primary system. The secondary LCRS is designed to remove the leakage from the primary system using a geonet drain material. The amount of leachate collected in the secondary LCRS is expected to be much smaller than the amount of leachate collected in the primary LCRS. The worst-case condition would be if the primary LCRS drain system was completely plugged and no longer functional and the level of the leachate in the cell would build up on the liner.

The leachate drain system is unlikely to fail during the early part of the cell design life, which is when most of the leachate will be generated. The leachate flow rate will decrease quickly during the first few years and approach a steady-state rate equal to the average cover infiltration rate.

The leakage rate was estimated using a method by Giroud (Giroud *et al.* 1989a, 1989b, 1992). Giroud concludes that, for small (less than 1 foot) hydraulic heads above the liner, leakage resulting from permeation through the geomembrane is negligible, and only leakage through defects in the geomembrane should be considered. The rate of leakage through a defect in the geomembrane depends on the size of the defect, the hydraulic head above the liner, and the quality of contact between the geomembrane and the underlying low-permeability soil layer.

Giroud *et al.* (1992) proposed an empirical equation for the leakage rate through a circular hole in the geomembrane component of a composite liner:

$$Q = .21 \cdot i_{avg} \cdot (a)^{0.1} \cdot (h)^{0.9} \cdot (K)^{0.74}$$

where

Q = the rate of leakage ;

a = geomembrane hole area;
h = head of liquid on top of the geomembrane; and
K = hydraulic conductivity of the low-permeability soil component of the composite liner

The average gradient i_{avg} is given by:

$$i_{avg} = 1 + E \cdot \frac{h}{t_{gcl}}$$

$$E = 1 + \frac{h}{(2 \cdot \ln(\frac{2 \cdot R}{b}))}$$

where

t_{gcl} is the thickness of the soil component
b is the diamter of the hole.

The term R, which is the radius of the wetted area of the low-permeability soil layer where flow takes place, is given by:

$$R = .26 \cdot (a)^{0.5} \cdot (h)^{.45} \cdot (K)^{-.13}$$

All units of length must be in meters and time must be in seconds.

The following assumed parameters were used in the Giroud equations to estimate the leakage through the disposal cell liner for this study:

• Hydraulic head on liner	30 cm
• Thickness of low-permeability soil (GCL)	0.25 in.
• Hydraulic conductivity of low-permeability soil	$3x10^{-09}$ cm/sec
• Area of a circular defect or hole	1 cm^2
• Contact between soil and geomembrane	good

The calculated leakage rate is 0.052 gal/day. More than one hole per acre can be expected, and it was assumed that the number of holes is small enough that the wetted area of leakage does not overlap. The equation (Giroud *et al.* 1992) estimates the radius of the wetted area. Using this estimate, the radius of the wetted area is 2.2 feet. Based on this estimate, only a single hole was modeled. This scenario is more appropriate than using an average leakage rate spread over the entire cell, assuming some number of holes or defects per acre. Using a single hole is more conservative than a cell-wide average because it concentrates the leakage from a hole over a smaller area, resulting in a higher rate than if the leakage from 10 holes per acre, for example, was averaged over the acre. Leakage was also estimated using a head of 1 meter to simulate leakage from the leachate collection sump where the depth of the leachate may be greater than in the collection system. The leakage rate for the sump was estimated to be about 0.41 gal/day with a wetted radius of 3.8 feet.

4.2 Leachate Chemistry

Laboratory batch tests for three waste forms (flocculated-raffinate-sludge grout, quarry-soil grout, and dike-soil mix) and a soil (radioactive soil) have been performed by PNL (Pacific Northwest Laboratory) to estimate the leachability of contaminants (Mattigod *et al.* 1995). The waste-form leachates were highly alkaline, containing mainly sodium, potassium, calcium, NO_2, NO_3, and SO_4. The test results are summarized in Table 1.

Table 1 Chemical Composition of Waste-Form Grout Leachate at 30 Days

Analyte	Concentration (mg/L)			
	Flocculated-Raffinate-Sludge Grout	Quarry-Soil Grout	Dike-Soil Mix	Radioactive Soil
Sodium	3,520	1,380	906	61.4
Potassium	1,830	540	89	16.7
Calcium	306	964	1,400	158
NO_2	400	1,300	216	<2.5
NO_3	6,000	4,300	4,100	<2.5

No nitroaromatic compounds were detected. When placed in contact with soils that are likely to be used in the seepage barrier, the ionic strength of the leachate was reduced 32% to 43%. Some trace constituents (cadmium, chromium, molybdenum, nickel, selenium, and zinc) were attenuated, while others (arsenic, cobalt, lithium, antimony, thallium, uranium, and vanadium) were enhanced. Equilibrium of the radioactive soil with simulated leachate released about 9% of ^{235}U and 8% ^{238}U, with leachate concentrations of 1,770 pCi/L and 35,750 pCi/L, respectively.

5.0 VADOSE ZONE COMPUTER MODEL

An unsaturated flow and transport computer model was used to simulate the flow of leachate from leaks in the disposal cell to the groundwater. The computer program used was the U.S. Geological Survey model VS2DT (Lappala *et al.* 1987 and Healy 1990).

5.1 Model Description

The program was used to simulate flow through the Ferrelview Formation and the clay till units. It was assumed that the topsoil and loess would be removed. The basal till and the residuum were not modeled because the presence of these units would not significantly add to travel time. The permeabilities of the basal till and the residuum are high relative to the modeled units, and these units are often not present or very thin.

Leakage was assumed to occur within a small area, such as from a hole in the liner, for example. The flow pattern was assumed to be symmetrical so that a two-dimensional radial grid could be used. The disposal cell is large, covering about 25 acres, so leakage was assumed to come from a single hole, because leakage from multiple holes would not overlap within a radius of 10 meters. The application of Giroud's equation (Giroud 1989a) indicates a wetted area with a radius of about 2.2 meters for this case.

A vertical, radially-symmetric grid 10 meters wide by 10 meters deep with 50 rows and 50 columns was selected. The grid is rotated about the leftmost edge to form a cylindrical section through the vadose zone. The computer program uses a block-centered solution method so that the pressure head and moisture content are determined at the center of each 0.2-meter block. Because of this block-centered method, the thickness of the vadose zone simulated by the model is 9.4 meters.

Recharge or leakage from the disposal cell was applied to the top row or at 0.1 meter. The leakage rate was determined using Giroud's equations as described in Section 4.1. A constant pressure equal to the head used in Giroud's equations was assigned to the cells in the top row, beginning with the first column and extending enough cells to the right so that the recharge rate to the model was approximately equal to the leakage rate determined by Giroud's equations. The radius of the applied recharge is approximately the same as Giroud's wetted area or 2.2 feet.

The water table was represented by assigning a fixed pressure head of zero to the bottom row of cells or at 9.5 meters. The initial moisture content of the model was determined, by the model, to be a static distribution of head above the water table to the top row. The moisture content varied from 0.4 (saturated) near the water table to 0.39 at the bottom of the disposal cell..

The model was used to simulate a base condition representing the expected parameter values as described in Section 5.2. The sensitivity of the model ouput to various parameters was evaulated by additional simulations described in Section 5.3.

5.2 Base Condition Input

For the base condition, the hydraulic conductivity was assumed to be $1x10^{-08}$ cm/sec. This value is larger than the average from the Boutwell two-stage borehole test and other tests, which was closer to $1x10^{-09}$ cm/sec, but slightly smaller than values reported in some laboratory tests (Daniel 1992).

Initial conditions were the steady-state conditions simulated using no recharge with the water table boundary, or essentially hydrostatic conditions above the water table. The initial chemical concentration of the vadose zone was assumed to be zero.

The soil-moisture-characteristic curve was determined from laboratory tests on samples of site soils. Because of the lower permeability and low effective porosity of the soils, the soils remained nearly saturated under hydrostatic conditions.

A transient simulation was run until the leachate outflow rate was equal to the inflow rate, or until steady-state flow conditions were reached. The travel time from the disposal cell to the groundwater was estimated to be the time required for the leachate to reach the lower boundary. However, in some cases, steady-state transport conditions were never reached, and the simulation was terminated at about 10,000 years.

The transverse and longitudinal dispersivity was assumed to be 0.1 meter. The dispersivity is highly site dependent and a function of scale. The coefficient of molecular diffusion for the porous medium was assumed to be 10^{-06} m^2/day. Molecular diffusion is dependent on the solute, temperature, and tortuosity. Site-specific data were not available for either dispersivity or molecular diffusion.

The distribution coefficient was assumed to be zero (no retardation), so that the travel time estimate would be more conservative (faster) than if some level of retardation was assumed. However, most of the contaminants of concern have been shown to have distribution coefficients, k_d, greater than zero (Schumacher 1993). The retardation coefficient is estimated from k_d as:

$$(1+\rho * k_d/\theta)$$

where

- ρ is the bulk density
- θ is the effective porosity

With the assumed conditions, the estimated retardation coefficient is 40 for a k_d of 1. No retardation was used in the base condition because, given the very low permeability, even a low k_d would result in moving the initial breakthrough time to a point that could be outside of the 10,000-year timeframe.

The concentration of the leachate inflow was assumed to be 1,000 gram/m^3 (1 gm/L) and constant for the full length of the simulation. The initial concentration of the vadose zone was assumed to be zero. The computer program input file for the base condition is shown in Table 2.

5.3 Sensitivity Analysis

The sensitivity of the model results to changes in several parameter values was evaluated. The following parameters were changed from the base condition:

- Hydraulic conductivity - 10^{-07} cm/sec
- Initial concentration - 200 g/m^3 (200 mg/L)
- Leakage rate - 0.41 gal/day
- Uniform leakage - pressure head of 30 cm along the top row
- Dispersivity - 1 meter
- Vadose zone thickness - 6 meters
- Hydraulic conductivity - 10^{-07} cm/sec
  - adsorption, k_d = 1 mL/gm

Table 2 VS2DT Computer Model Input - Base Condition

Parameters	*Card Number*
400000000. 0. 0.	A2--TMAX,STIM,ANG
M DAYGRAM	A3--ZUNIT,TUNIT,CUNX
50 50	A4--NXR,NLY
3 1000	A5--NRECH,NUMT
T T T	A6--RAD,ITSTOP,TRANS
T T F	A6A--CIS,CIT,SORP
T F T T F	A7--F11P,F7P,F8P,F9P,F6P
T F F F T	A8--THPT,SPNT,PPNT,HPNT,VPNT
1 .2	A9--IFAC,FACX
1 .2	A11--IFAC,FACZ
1	A13--NPLT
365000.	A14
1	A15 nobs.
49 2	A16 row, col
4	A17-NMB9
3 6 54 57	A18-MB9
.00000001 1.0 0.00 0.00000001	B1--EPS,HMAX,WUS,EPS1
2 100	B3--MINIT,ITMAX
T	B4--PHRD
1 6 7	B5--NTEX,NPROP,NPROP1
1	B6--ITEX
1. 8.64E-06 0. .402 -11.12 .352 1.952	B7--ANIZ,HK
.1 .1 1.0E-06 0. 0. 0. 0.	B7A--HT
1	B8--IROW
1 50 50 1	B10--IL,IR,JBT,JRD
2 0	B11--IREAD,FACTOR
9.5 -1000	B12--BWTX,HMIN
F F	B15--NPV,ETCYC
0 0.	B24--IREAD,FACTOR
3650 365. Recharge Period 1	C1--TPER,DELT
1.0 10000. 10. 1.0	C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.0001	C3--DSMAX,STERR
1000.	C4--POND
F	C5--PRNT
F F F	C6--BCIT,ETSIM,SEEP
1	C10--IBC
2 2 2 2 0 0 0 0	C11--JJ,NN,NTX,PFDUM,NTC,CF
49 49 2 49 1 0 0 0	
999999 /	C13
365000. 365. Recharge Period 2	C1--TPER,DELT
2 36500. 10. 1.0	C2--TMLT,DLTMX,DLTMIN,TRED
100. 0.0001	C3--DSMAX,STERR
0.	C4--POND
F	C5--PRNT
F F F	C6--BCIT,ETSIM,SEEP
1	C10--IBC
2 2 2 6 1 .30 0 1000	C11--JJ,NN,NTX,PFDUM,NTC,CF
49 49 2 49 1 0 0 0	C12
999999 /	C13
999999 /	C13

6.0 SUMMARY OF MODELING RESULTS

6.1 Base Condition

The model was run with no leachate inflow until steady-state conditions were reached. The base simulation at a constant solute inflow rate with a concentration of 1,000 gram/m^3 was run using the steady state as initial conditions. The mass balance summary for the modeling results at the end of 5,000 years is presented in Table 3. The initial vadose zone concentration was assumed to be zero. These values represent steady-state flow conditions. The inflow rate and outflow rate are both about 2x10^{-04} m/day or about 0.052 gal/day. However, the solute mass balance is far from a steady-state condition. The solute mass inflow rate is about 0.2 grams/day, while the outflow rate is only 3.2x10^{-9}, or essentially zero. Both the flow and solute mass balance errors are less than 1%, which is acceptable.

The solute volume and mass flow mass balance for various simulation times are shown in Table 4. The solute volume outflow rate was about 43% of the inflow rate at the end of 30 years, and 99% at the end of about 326 years.

The solute mass outflow rate is essentially zero until about 3,000 years, when the mass flux begins to increase more rapidly (Figure 3). The mass balance summary (Table 3) shows a total solute mass inflow of 0.2 grams/day and mass outflow of 0.09 grams/day after 10,000 years.

The moisture distribution in the vadose zone at the end of the simulation period is shown in Figure 4. The moisture content is at saturation near the water table and in the area directly beneath the simulated leakage. Comparing the moisture content with Figure 1 shows that, even over the small range of values shown, the hydraulic conductivity varies almost an order of magnitude lower than the saturated hydraulic conductivity. The moisture distribution shows that the simulated leakage spreads laterally away from the source a short distance, but remains within the 10-meter radius of the modeled area.

The model simulation results indicate that there is an immediate increase in the outflow of water across the lower boundary to the groundwater table. Table 4 shows that the volume outflow rate jumps from 0 at the instant the simulated leakage inflow is applied to 2.7x10^{-4} gm/day at the end of 2 years, and gradually rises over time to equal the inflow rate. However, the outflow of water is not the leakage applied at the upper boundary, but rather is the water in the unsaturated zone prior to applying the leakage. The outflow pulse is similar to a pressure response in a confined aquifer system. Gelhar (1993) uses a linear, unsaturated flow model to show that the rate of propagation of a moisture pulse to the groundwater table will generally be faster than the moisture flux itself. The addition of moisture produces a pressure disturbance that propagates rapidly downward through the unsaturated zone due to the steep slope of the hydraulic conductivity-moisture content curve at a high moisture content.

The arival of the applied leakage at the lower boundary should be evidenced by an increase in the mass outflow rate. However, the model simulation results show that there is essentially no contaminant mass outflow at the lower boundary for an initial vadose zone concentration of zero. When the initial vadose zone concentration was increased to 200 grams/m^3, the solute mass outflow was equal to the initial vadose zone concentration. No increase from that level was observed, which indicates that the ouflow did not include any of the applied leachate water.

6.2 Sensitivity Analysis

The sensitivity of the model to hydraulic conductivity was tested by increasing the hydraulic conductivity from $1x10^{-8}$ cm/sec to $1x10^{-7}$ cm/sec and repeating the simulation. The resulting mass flux rate is shown in Figure 3. The arrival of the solute begins in about 500 years instead of 3,000 years, as in the previous simulation. The higher conductivity increased the flow rate as expected, and equilibrium conditions between inflow and outflow were reached after 6,000 years.

The base simulation was repeated with an initial vadose zone concentration of 200 grams/m^3 (Table 5). The values represent steady-state flow conditions. The inflow rate and outflow rate are both about $2x10^{-04}$ m^3/day, or about 0.052 gal/day. The solute mass flux outflow is close to steady-state conditions. The solute mass inflow rate is the same as with an initial concentration at zero, about 0.2 grams/day, but the outflow rate has increased from $3.2x10^{-09}$ to $3.9x10^{-02}$. However, the mass inflow rate is still almost 10 times greater than the outflow rate. Both the flow and solute mass balance errors are less than 1%, which is acceptable.

A model simulation was run to simulate a uniform leakage rate across the disposal cell area compared to a point source or hole in the liner. A head of 30 cm was applied to the upper layer of the model. The hydraulic conductivity was kept at $1x10^{-08}$ cm/sec. The results are shown in Figure 3. Leachate breakthrough occured at about 600 years, much earlier than the previous simulation of a leakage from a hole in the liner. This simulation shows a more typical breakthrough curve than the other simulations, because the uniform nature of the recharge is more representative of the one-dimensional analytical equations that are used to simulate chemical transport. As would be expected, the steady-state inflow rate is equivalent to the flow calculated for a unit gradient at the hydraulic conductivity of $1x10^{-08}$ cm/sec. Travel time would be about 1,300 years, assuming a unit gradient and the porosity and hydraulic conductivity used in the simulation. Simulated steady-state conditions were reached in about 1,900 years. The difference between the simulated travel time and the estimated travel time is due to hydrologic and numerical dispersion. In comparison, steady-state conditions for the point source simulation were not reached in 10,000 years.

The base condition head was increased from 30 cm to 1 meter to allow for the higher heads expected in the sump. Using Giroud's equation, the leakage was estimated to be about 0.41 gal/day, which was higher than the 0.052 gal/day used in the base condition. The distribution of the head in the upper layer of the model was adjusted (the number of cells were increased) to achieve the leakage rate and radius of the wetted area suggested from Giroud's equation. The results of the simulation for leakage from the leachate collection sump are shown in Figure 3. The mass flux rate increased as expected, but still did not reach steady-state conditions within 10,000 years. Initial breakthrough occured earlier than with the lower head, at about 2,000 years instead of 3,000 years.

A simulation was run with the vadose zone thickness decreased from 10 meters to 6 meters. The results are shown in Figure 5. The initial breakthrough time was much earlier, at about 900 years, with the 6-meter thickness than with the 10-meter thickness, at about 3,000 years.

A simulation was run with the dispersivity set to 10 times the base condition of 0.1 for the longitudinal and transverse dispersivity. The breakthrough occured sooner than in the base condition--about 2,000 years compared to 3,000 years (Figure 5). However, the shape of the breakthrough curve was flatter and broader than in the base condition, as was expected for the larger value of dispersivity. The larger value of dispersivity causes the breakthrough curve to smear, with the initial breakthrough occuring earlier but with the maximum concentration occuring later. The midpoint on the breakthrough curve will be the about same for any value of dispersivity.

The solute concentration in the vadose zone at the end of the period is shown in Figure 6. The concentration decreases radially from 1,000 grams/m^3 at the source to 0 within about 2 meters of the groundwater table located at the bottom of the figure.

The effect of retardation was evaluated by using the linear Freundlic isotherm and a k_d value of 1 mL/gram. The hydraulic conductivity was assumed to be $1x10^{-07}$ cm/sec, rather than the base condition value of $1x10^{-08}$ cm/sec, so that the effects would be more visible within the 10,000-year simulation period. The results are shown in Figure 7. The effect of retardation was to delay the breakthrough until 1,200 years instead of 500 years and reduce the overall mass outflow rate to the groundwater table. Steady state was not reached within the 10,000-year simulation. The outflow was reduced by adsorption onto the vadose zone soil. The adsorption rate was about 1.4 grams/day until after about 1,200 years, and then gradually declined to 0.2 gram/day as the adsorption capacity of the soil was depleted.

Table 3 Base Condition Mass Balance Summary

VOLUMETRIC FLOW BALANCE	TOTAL M**3	TOTAL THIS TIME STEP M**3	RATE THIS TIME STEP M**3/ DAY
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	7.86118E+02	5.28719E+00	1.95749E-04
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	-7.83170E+02	-5.28711E+00	-1.95747E-04
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX INTO DOMAIN --	7.86118E+02	5.28719E+00	1.95749E-04
TOTAL FLUX OUT OF DOMAIN --	-7.83170E+02	-5.28711E+00	-1.95747E-04
EVAPORATION --	0.00000E+00	0.00000E+00	0.00000E+00
TRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL EVAPOTRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN FLUID STORED IN DOMAIN --	2.93719E+00	0.00000E+00	0.00000E+00
FLUID VOLUME BALANCE --	1.01193E-02	7.28778E-05	2.69818E-09

SOLUTE MASS BALANCE	GRAM	GRAM	GRAM/ DAY
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	7.86118E+05	5.28719E+03	1.95749E-01
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	-1.39901E+05	-2.54899E+03	-9.43722E-02
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
DIFFUSIVE/DISPERSIVE FLUX INTO DOMAIN --	0.00000E+00	0.00000E+00	0.00000E+00
DIFFUSIVE/DISPERSIVE FLUX OUT OF DOMAIN --	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX INTO DOMAIN --	7.86118E+05	5.28719E+03	1.95749E-01
TOTAL FLUX OUT OF DOMAIN --	-1.36767E+05	-2.53099E+03	-9.43722E-02
TOTAL EVAPOTRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
FIRST ORDER DECAY --	0.00000E+00	0.00000E+00	0.00000E+00
ADSORPTION/ION EXCHANGE --	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN SOLUTE STORED IN DOMAIN --	6.47626E+05	2.78487E+03	1.03105E-01
SOLUTE MASS BALANCE --	1.72436E+03	-2.86721E+01	-1.06153E-03

Table 4 Volume and Mass Flow Rates Across Model Boundaries (Zero Initial Contamination)

Elapsed Time (years)	Inflow Rate (m3/day)	Ouflow Rate (m3/day)	Mass Inflow Rate (grams/day)	Mass Outflow Rate (grams/day)
2	2.694e-04	-4.634e-07	2.694e-01	-7.778e-78
6	2.192e-04	-7.198e-06	2.192e-01	-8.679e-72
14	2.063e-04	-3.501e-05	2.063e-01	-6.683e-56
30	2.004e-04	-8.669e-05	2.004e-01	-4.674e-42
62	1.975e-04	-1.418e-04	1.975e-01	-1.217e-30
126	1.963e-04	-1.783e-04	1.963e-01	-1.225e-21
226	1.959e-04	-1.917e-04	1.959e-01	-1.027e-16
326	1.958e-04	-1.948e-04	1.958e-01	-3.749e-15
426	1.958e-04	-1.955e-04	1.958e-01	-6.645e-14
526	1.958e-04	-1.957e-04	1.958e-01	-7.722e-13
626	1.957e-04	-1.957e-04	1.957e-01	-6.641e-12
726	1.957e-04	-1.957e-04	1.957e-01	-4.515e-11
826	1.957e-04	-1.957e-04	1.957e-01	-2.529e-10
926	1.957e-04	-1.957e-04	1.957e-01	-1.201e-09
990	1.957e-04	-1.957e-04	1.957e-01	-2.819e-09
1000	1.957e-04	-1.957e-04	1.957e-01	-3.192e-09
2000	1.957e-04	-1.957e-04	1.957e-01	-2.965e-05
3000	1.957e-04	-1.957e-04	1.957e-01	-1.323e-03
4000	1.957e-04	-1.957e-04	1.957e-01	-7.706e-03
5000	1.957e-04	-1.957e-04	1.957e-01	-1.963e-02
10000	1.957e-04	-1.957e-04	1.957e-01	-8.493e-02

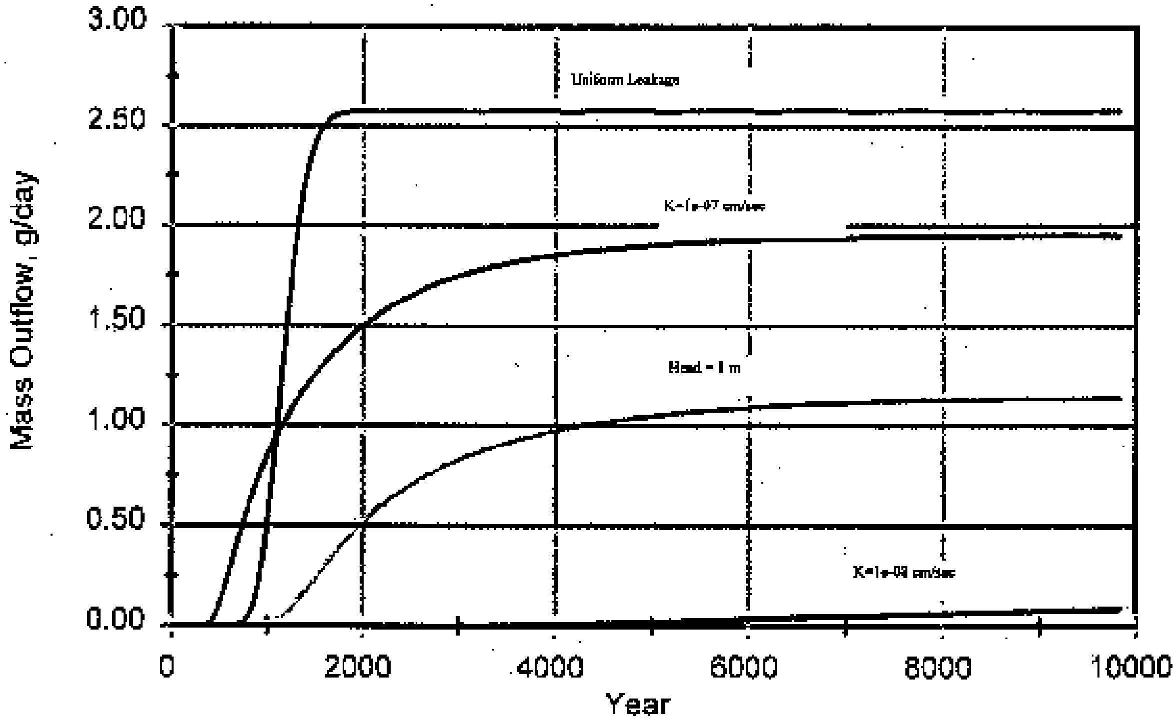

Figure 3 **Solute Mass flow for Base Condition, Head, K, and Leakage**

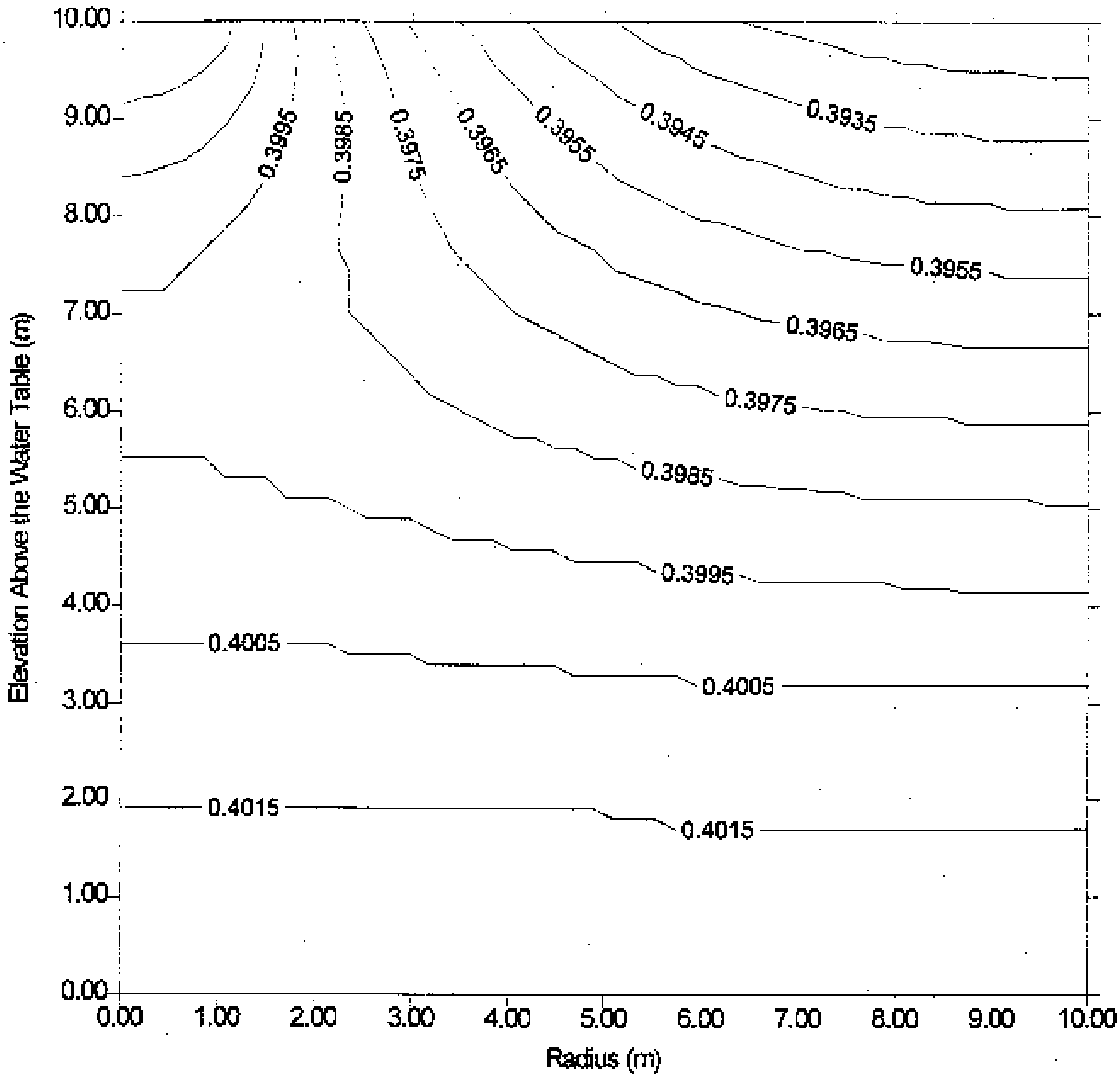

Figure 4 Simulated Volumetric Moisture Content After 1000 Years (porosity = .402)

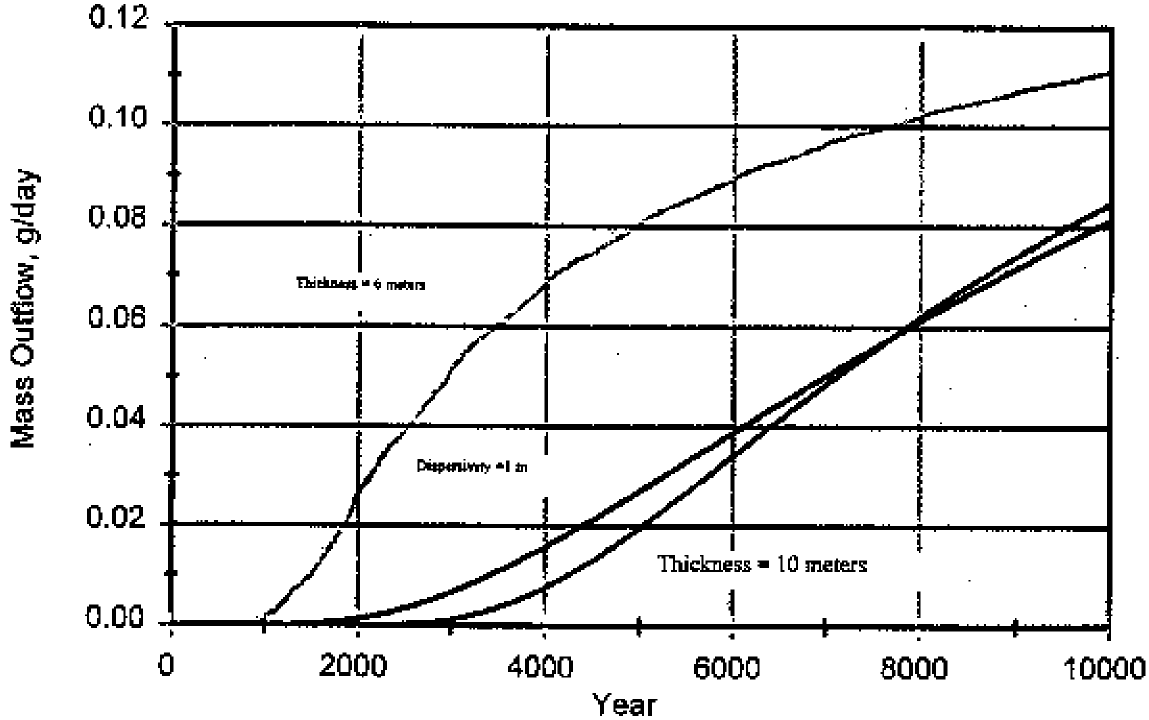

Figure 5 **Solute Mass Flux for Base Condition, Thickness, and Dispersivity**

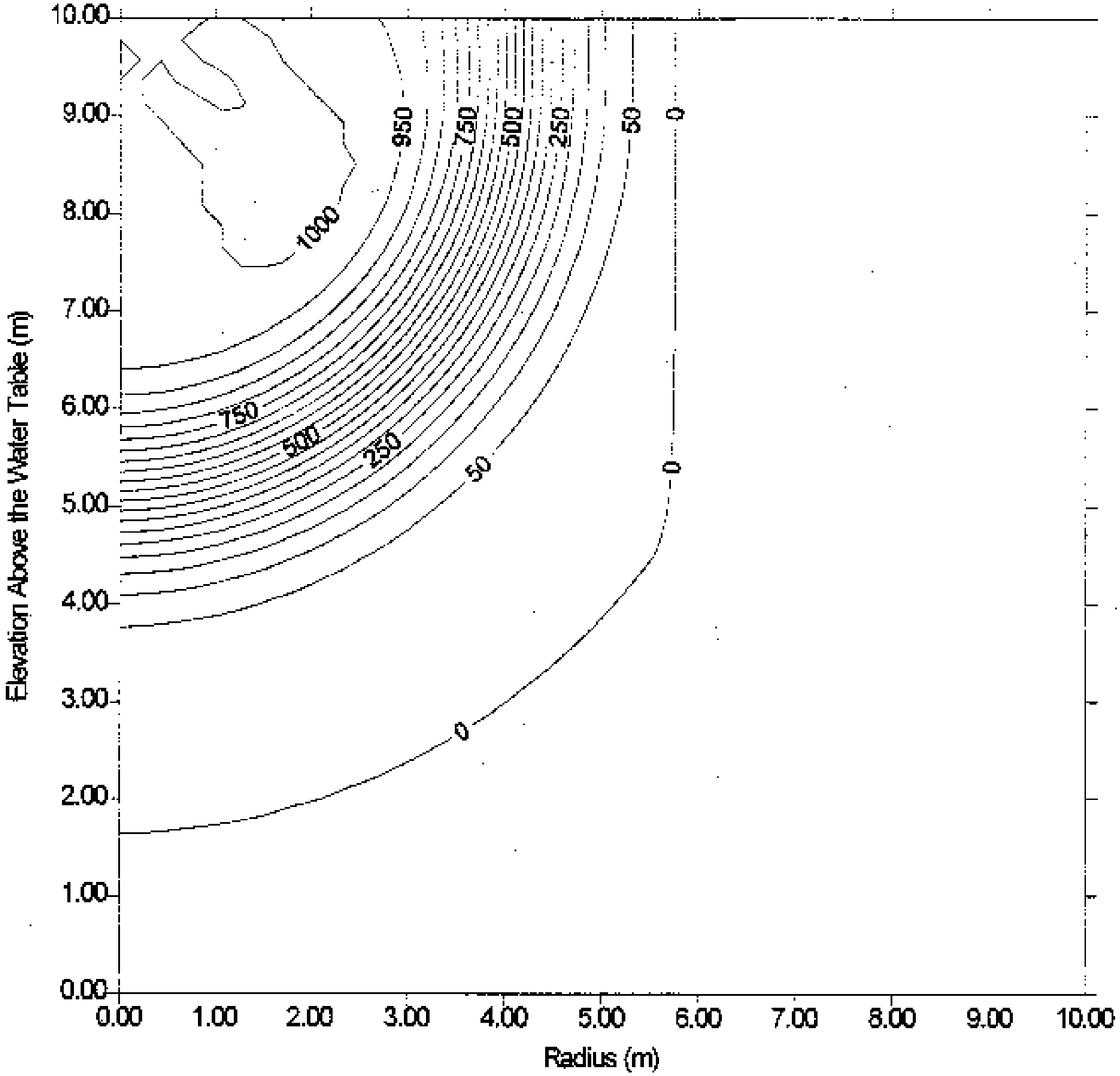

Figure 6 **Simulated Solute Concentration in grams/m³ After 1000 Years**

Table 5 Volume and Mass Flow Rates (200 grams/m^3 Initial Contamination)

Elapsed Time (years)	Inflow Rate (m^3/day)	Outflow Rate (m^3/day)	Mass Inflow Rate (grams/day	Mass Outflow Rate (grams/day)
2	2.694e-04	-4.634e-07	2.694e-01	-9.267e-05
6	2.192e-04	-7.198e-06	2.192e-01	-1.440e-03
14	2.063e-04	-3.501e-05	2.063e-01	-7.002e-03
30	2.004e-04	-8.669e-05	2.004e-01	-1.734e-02
62	1.975e-04	-1.418e-04	1.975e-01	-2.837e-02
126	1.963e-04	-1.783e-04	1.963e-01	-3.566e-02
226	1.959e-04	-1.917e-04	1.959e-01	-3.834e-02
326	1.958e-04	-1.948e-04	1.958e-01	-3.896e-02
426	1.958e-04	-1.955e-04	1.958e-01	-3.911e-02
526	1.958e-04	-1.957e-04	1.958e-01	-3.914e-02
626	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02
726	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02
826	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02
926	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02
990	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02
1000	1.957e-04	-1.957e-04	1.957e-01	-3.915e-02

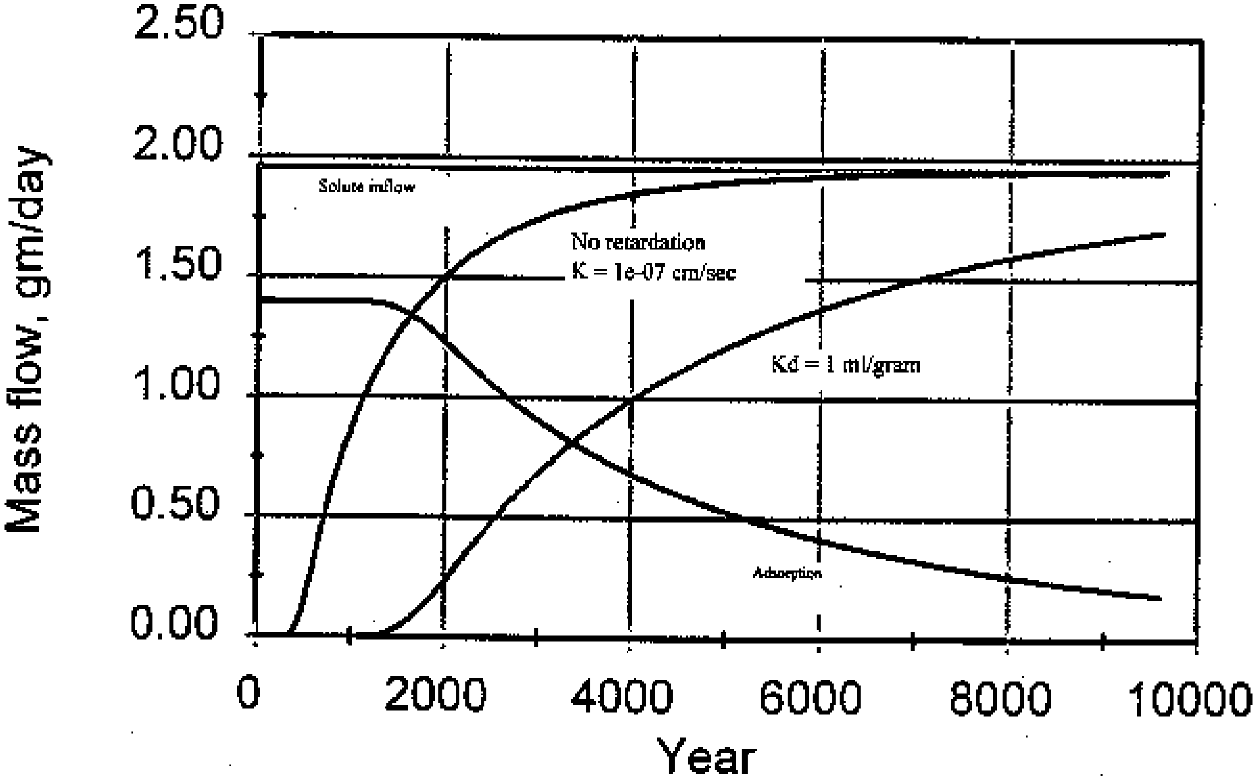

Figure 7 **Comparison of Solute Mass Flow With Adsorption**

7.0 CONCLUSIONS

The unsaturated flow computer program VS2DT was used to simulate the flow of leachate from the disposal cell through the vadose zone to the groundwater table. The program was used to estimate the travel time to the water table for various hydrologic conditions. Simulations were run to test the sensitivity of the estimated travel time to changes in hydraulic conductivity, vadose zone thickness, leakage rate, and dispersivity. The simulations were run for 10,000 years.

The parameter values for the base condition were a hydraulic conductivity of $1x10^{-08}$ cm/sec, a thickness of 10 meters, and a leakage rate of 0.05 gal/day simulated with a head of 30 cm over a limited area, as suggested by Giroud's equations. The base condition parameter values were assumed to represent the most likely condition. Other simulations were run to evaluate the sensitivity of the model to the selected parameters. Hydraulic conductivity was increased to $1x10^{-07}$ cm/sec, head was increased to 1 meter, and the thickness was reduced to 6 meters for the other simulations. The effect of a uniform leakage rate was also simulated with a 30-cm head applied across the entire upper model boundary. Dispersivity was increased by a factor of 10 from 0.1 meter to 1 meter.

The simulations show that the initial pulse of flow from the vadose zone to the aquifer occurs earlier than the mass flux breakthrough. Steady-state outflow in the base condition occurs at the simulated groundwater table after about 300 years, compared to 3,000 years for the first leachate to arrive. The early flow pulse is a characteristic of piston-like flow where pressure caused by the inflow at one end of a path pushes water out the at the other end of a path.

Among the parameters evaluated, the simulated leachate travel time or breakthrough time is most sensitive to the hydraulic conductivity and least sensitive to the dispersivity. The vadose zone thickness is an important factor, but it is not as important as the hydraulic conductivity.

The simulations indicate that the quantity of leakage has a significant impact on the travel time for leakage to flow from the cell to the water table. Although the uniform leakage simulation is not likely to occur, it represents a leakage rate of about 11 gal/acre per day or 0.15 inch/year across the entire cell and would require 100% failure of the liner system.

The breakthrough time for the base condition occurs at about 3,000 years. The earliest simulated breakthrough occurs at about 300 years with the hydraulic conductivity at $1x10^{-07}$ cm/sec. However, the leachate may not be detectable in the groundwater at the mass flux rate associated with that time. With the reduced vadose zone thickness, the initial breakthrough occurs at about 900 years, but the maximum flux rate is less than when the hydraulic conductivity is $1x10^{-07}$ cm/sec. Increasing the head, and consequently the leakage rate, to 1 meter moved the breakthrough time up to about 2,000 years. With a uniform leakage rate, the breakthough time was 600 years. The dispersivity of 1 meter increased the breakthrough time from 3,000 years to about 2,000 years.

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