NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

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Effects of Hydrocarbon Spills from an Oil Pipeline Break on Ground Water

by

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August 3, 1993

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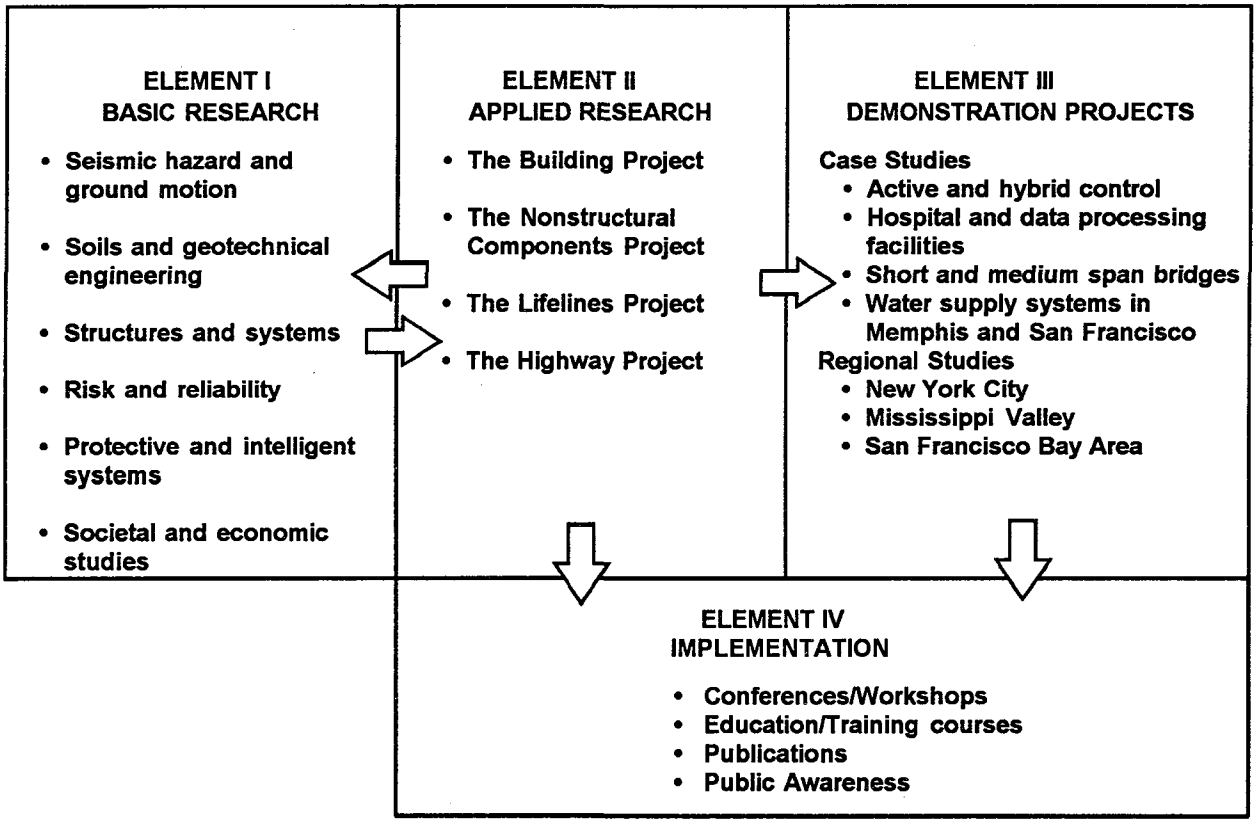
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.



Research tasks in the **Lifeline Project** evaluate seismic performance of lifeline systems, and recommend and implement measures for mitigating the societal risk arising from their failures or disruption caused by earthquakes. Water delivery, crude oil transmission, gas pipelines, electric power and telecommunications systems are being studied. Regardless of the specific systems to be considered, research tasks focus on (1) seismic vulnerability and strengthening; (2) repair and restoration; (3) risk and reliability; (4) disaster planning; and (5) dissemination of research products.

The end products of the **Lifeline Project** will include technical reports, computer codes and manuals, design and retrofit guidelines, and recommended procedures for repair and restoration of seismically damaged systems.

This report presents the results of a risk assessment of a potential crude oil pipeline break and resulting hydrocarbon spill on the West Tennessee aquifer caused by a seismic event in the New Madrid area. The study investigated the liquefaction potential at the pipeline crossing of the Wolf River, simulated the postulated oil spill using the computer programs ARMOS and MOFAT, evaluated the surface water/basin impacts, and provided a remediation strategy.

The study found that infiltration, distribution and dissolution from hydrocarbon spills is slow, which would allow ample time for remediation should such a spill occur. However, the remediation effort must be complete to ensure that no health hazard exists.

ABSTRACT

The study was undertaken to determine the effect of an oil spill, which might be caused by a seismic event rupturing a crude oil pipe line which crosses the recharge area of the Memphis Sands Aquifer. To do this, two numerical models were used to simulate a potential rupture to the 40 inch crude oil pipeline located in Wolf River fluvial valley susceptible to liquefaction. The spilled crude oil could have detrimental effects on the ground water quality, especially impacting the Memphis Sands Aquifer.

The simulation approach used two two-dimensional upstream weighted finite element models to predict the three-dimensional flow phenomenon of released crude in the unsaturated and saturated zones. ARMOS (Areal Multiphase Organic Simulator) was used to simulate the crude oil migration horizontally and to evaluate the extent of the crude dispersion on the ground water table. MOFAT (Multiphase Organic Flow And Transport) was used to simulate crude oil saturation in the vertical flow domain, in order to evaluate the dissolution of particular monoaromatic hydrocarbon isomers such as Benzene, Toluene, Ethylbenzene and Xylene (BTEX) in the ground water system.

The simulated results aided in designing an appropriate strategy for site remediation. ARMOS predicted a plume covering an area of about 10,800 square meters after 10 days of migration. The plume covered a maximum area of about

18,800 square meters after 30 days of migration. MOFAT predicted the most soluble species, toluene, dispersing with the highest phase concentration of 0.20 kilogram per cubic meters at distances of 56, 79, 102, and 130 meters away from the spill site over the periods of 30, 60, 90 and 120 days of redistribution. The amount of BTEX's present in the ground water was significant and would require prompt remediation action to contain ground water contamination.

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1.1 Purpose and Scope of Study

The purpose of the study was to determine the impact of an oil spill from a crude oil pipeline ruptured by an earthquake. In order to do this, a probable spill site and scenario was chosen along with reasonable assumptions concerning the location of the break, soil characteristics, and crude oil make up. In case of such an oil spill, the risks and potential environmental impacts need to be analyzed in order to take preventative action and be prepared to remediate the site when the rupture occurs.

The geographic location (to be described later) was in West Tennessee where a major pipe line crosses several rivers. Since the probable cause of pipe rupture would be liquefaction and the soil most susceptible to liquefaction is in the fluvial deposits or river flood plains, the flood plain of the Wolf River was chosen to demonstrate the results of such a rupture. Other reasons for choosing this area are; the largest pipeline in the United State crosses it; it is near the New Madrid Fault; and the pipeline crosses the recharge area of the Memphis Sands Aquifer, which is the main water supply for the Memphis area. The study results were to give (as far as possible) quantitative predictions of the environmental impacts of an oil spill in order to determine the danger, risk, and best remediation measures. In order to do this, the probable volume of oil to be spilled was determined. The flow of this oil was then estimated by running two finite element simulation models, ARMOS and MOFAT [2, 3, & 4]. Two probable pipe rupture sites were chosen, one under the Wolf River and one at the edge of the flood plain. The impacts from these two sites for two river stages were then evaluated, one when the river was at flood stage during the

high flow period and the other during the normal low flow period.

Special attention was given to possible long term effects from soluble hydrocarbons such as Benzene, Toluene, Ethylbenzene and Oxylene. The results were to give qualitative knowledge of impacts of similar sites both near the New Madrid Fault Zone and on other areas.

1.2 Site Description and Definition

The proposed rupture zone is where the 40 inch Shell Pipeline 22, also called "Capline," crosses the Wolf River near the Shelby/Fayette County line which is north east of Memphis, Tennessee. It transports approximately 230 million barrels of crude oil per year from the Gulf of Mexico and Louisiana to the refineries in St. Louis, Chicago, Toledo, Detroit, Buffalo and Canada [5]. The approximate location of the pipeline and the study area are shown in Figure 1-1. Figure 1-1 also shows that the pipeline crosses two potential pipeline rupture zones. The first rupture scenario is in the channel bed under the Wolf River and the second one is in the edge of the wetland that is about 1.6 kilometers (1 mile) from the river. The pipeline is buried about 1.22 meters (4 feet) under the ground. The profile of this pipeline across Wolf River and flood plain is shown in Figure 1-2.

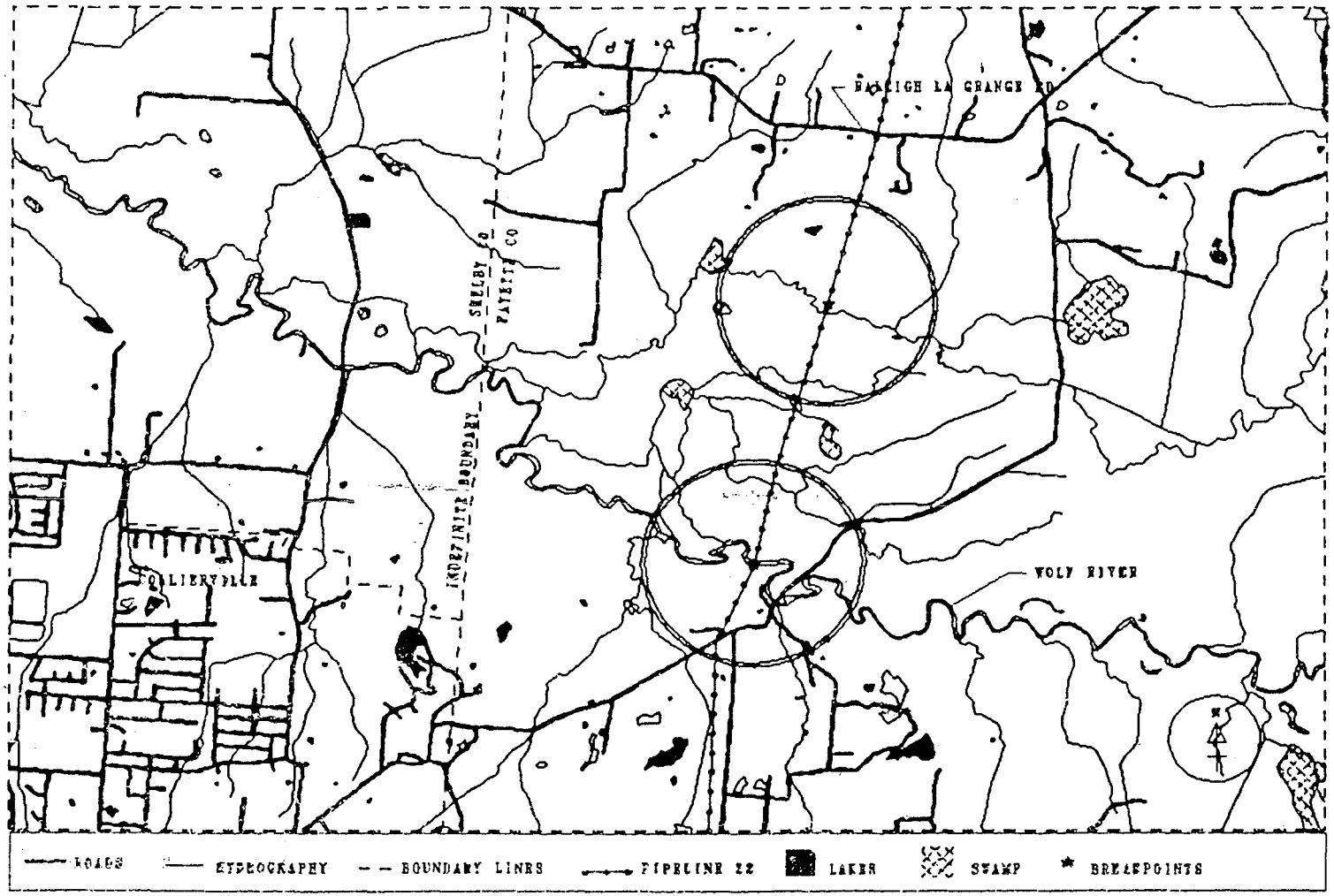

Figure 1-1 Land Features and Pipeline Location of Study Area

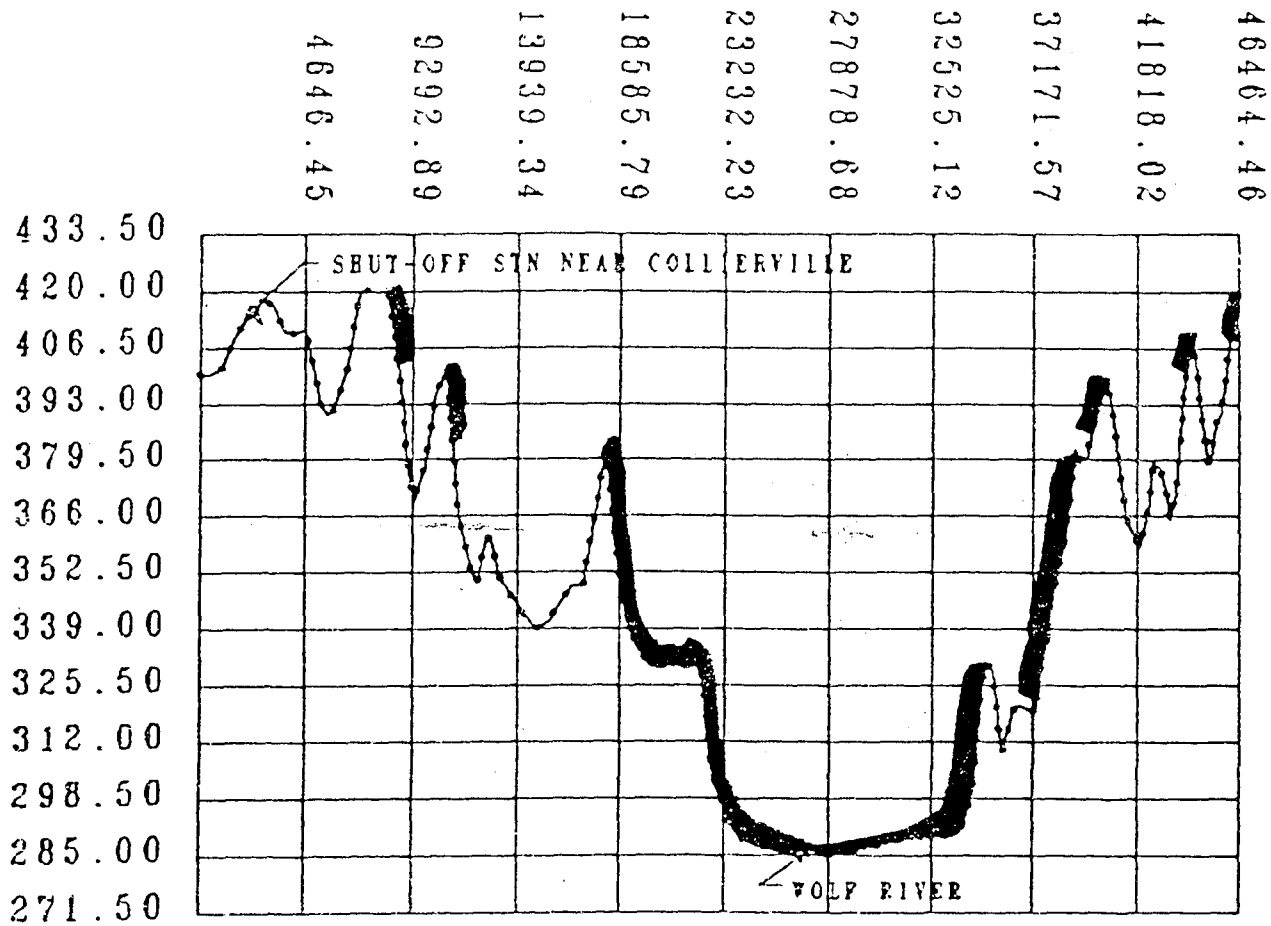

Figure 1-2 Profile of Pipeline 22 Across Wolf River and Flood Plains Between the Ridges Bracketing the Study Area

Pipeline 22 is considered the most vulnerable pipeline among the several pipelines which are close to the study area because it is the largest and is near to the New Madrid Zone [6]. The approximate locations of these major crude oil pipelines are shown in Figure 1-3 [7]. The profile of pipeline 22 in this study area is shown in Figure 1-4. This profile extends between two shut-off valves. One of the valves is located in Collierville and the other one is located in Brownsville. The segment of the pipeline between these valves is about 88,514 meters (55 miles). Moreover, the pipeline crosses the recharge area to the Memphis Sands Aquifer as shown in Figure 1-5.

The Memphis Sand Aquifer (MSA) is the most extensively used aquifer in Shelby County since initial withdrawal from the aquifer in 1886. The aquifer yields about 757,400 cubic meters per day (200 million gallons per day). The major user of this aquifer is Memphis Light Gas and Water (MLGW) which supplies water for municipal use to the City of Memphis and other areas within the county. The formation lies from zero to 152.4 meters (500 feet) below ground surface and ranges from 152.4 to 271.3 meters (500 to 890 feet) thick [8]. Most of the aquifer is protected by the Jackson Clay formation.

1.3 Scenario Analysis and Magnitude of Spill

As stated previously, there were four possible scenarios considered for analysis; high flow, break under the river; high flow, break in the wet lands, low flow, break under the river; and low flow, break in the wet lands. Of these, only one poses a

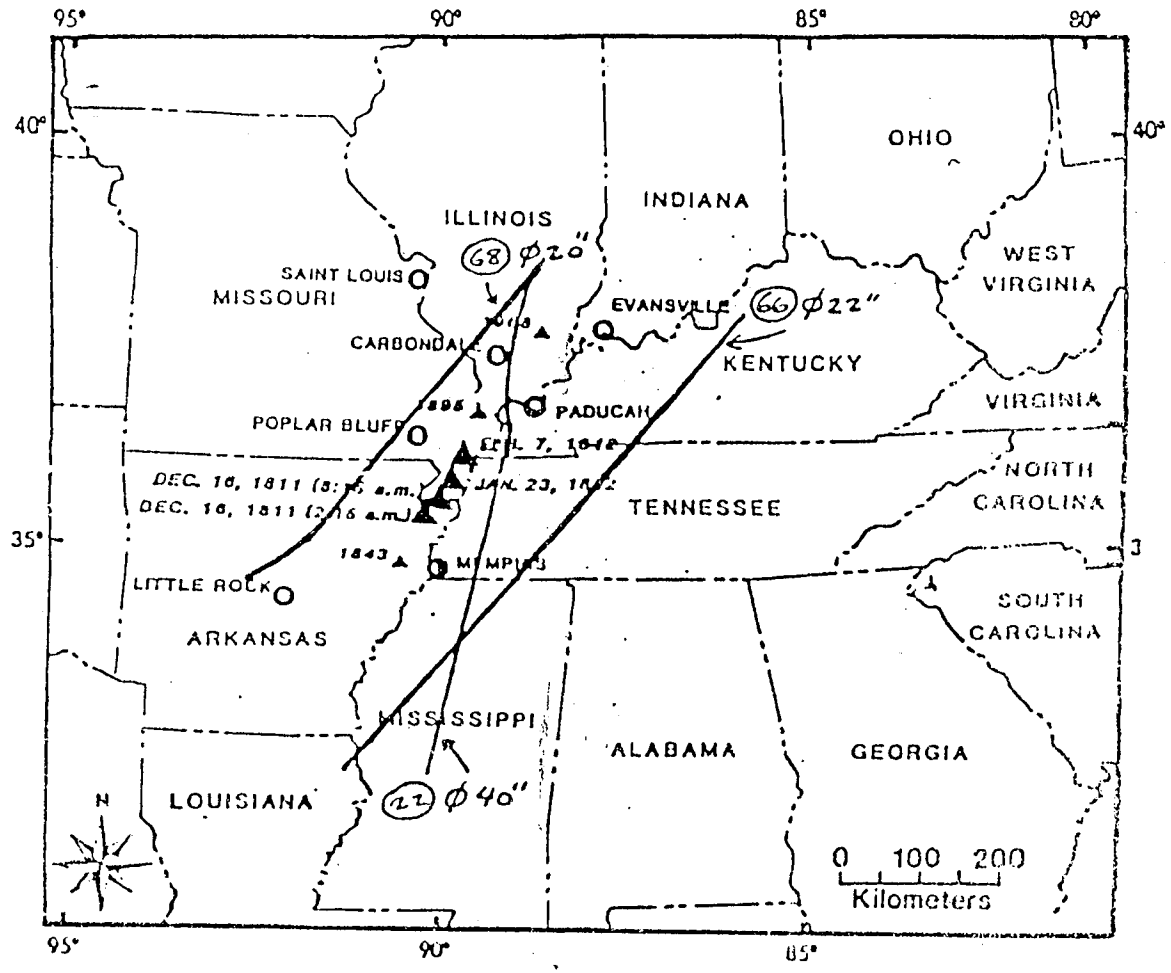

Figure 1-3 Epicenters of 1811-12 New Madrid Earthquakes and Approximate Locations of Oil Transmission Pipelines [7]

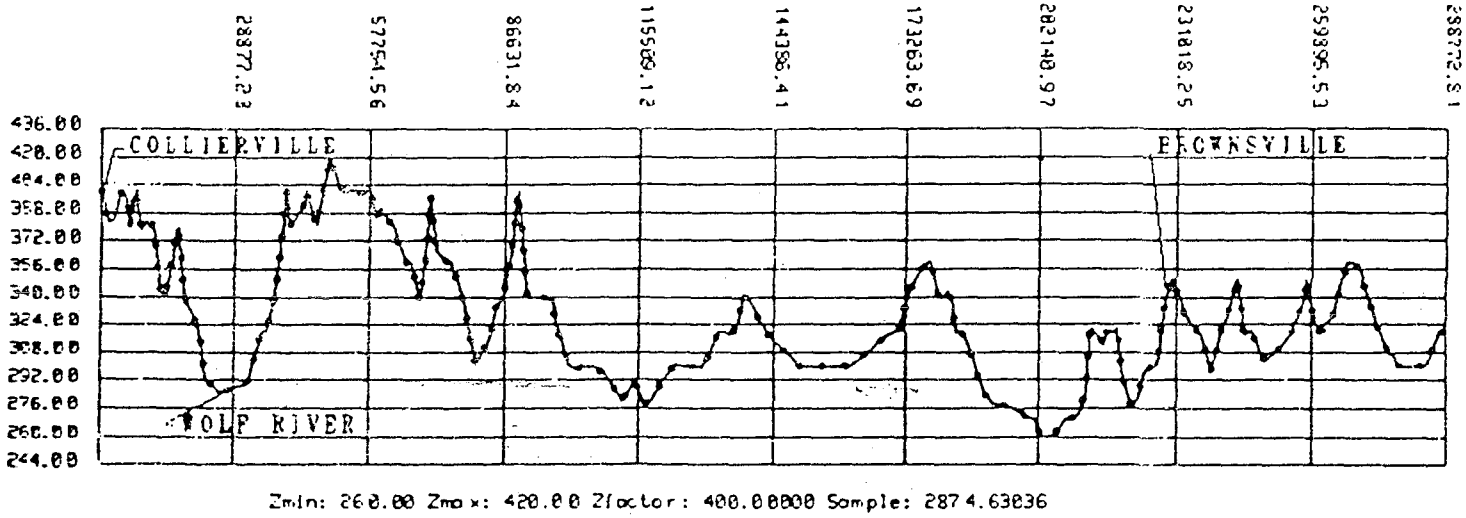

Figure 1-4 Profile of Pipeline 22 Between Collierville and Brownsville

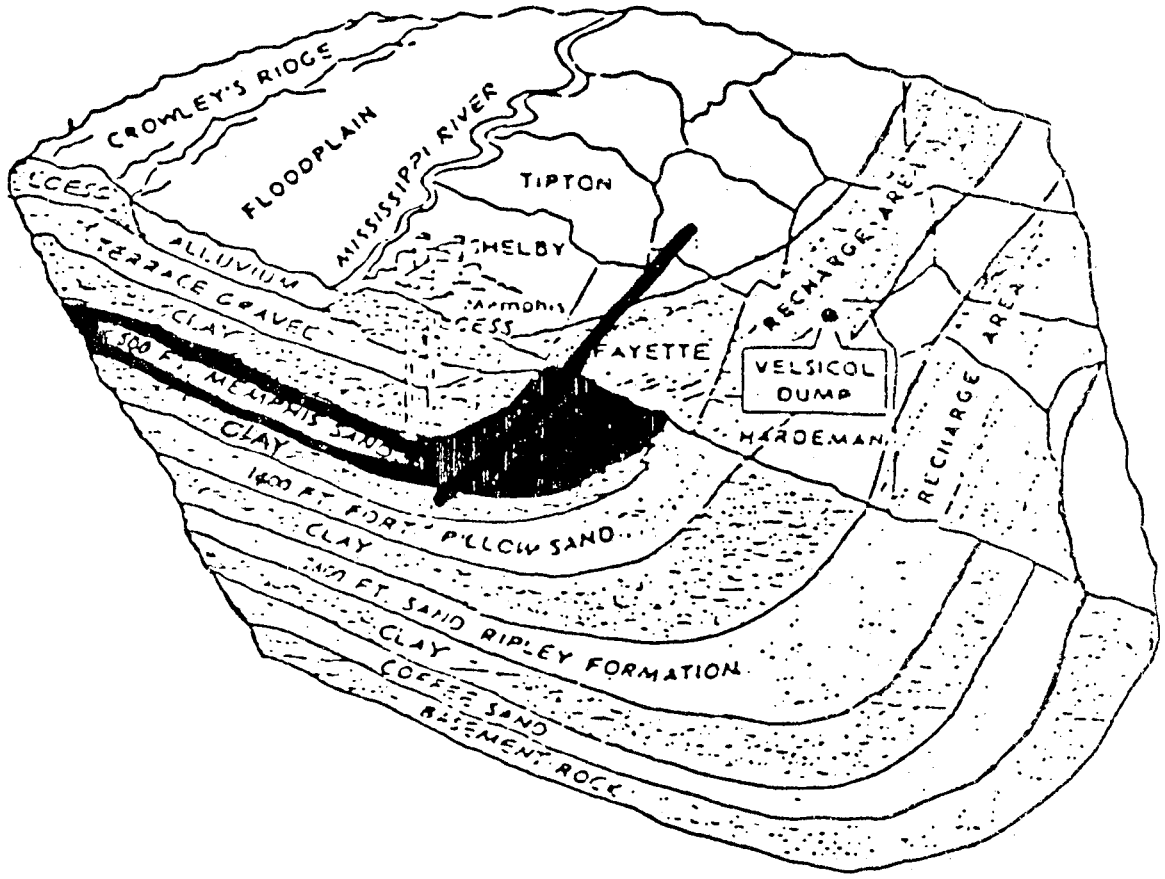

Figure 1-5 Profile of the West Tennessee Aquifers

significant danger to the aquifer, ie. the low flow, break in the wet lands. Breaks under the river or a break in the wet lands during high flow, will release all the NAPL into the surface water system for transport downstream. Because the crude oil, NAPL, is lighter than water and potential (pressure) gradient is from the aquifer up and into the surface water, the floating plume of crude oil will be carried downstream by the river.

The NAPL on the surface water system was estimated to flow at minimum velocity of 0.76 meter per second (2.5 feet per second) and at maximum velocity of 1.98 meter per second (6.5 feet per second). The travel time of the plume will take approximately 18 hours at minimum flow velocity and 7 hours at maximum velocity to reach the discharge point at the Mississippi River. This scenario will be detailed in a separate report.

The fourth scenario, the pipe ruptured at the edge of the flood plain during the normal low flow period, was the one chosen for this study. The spilled hydrocarbon would be on land and migrate downward causing subsurface contamination. This latter scenario was taken as the worst case scenario to be modeled.

The estimated volume of oil contained in the segment of 88,514 meters (55 miles) long pipe line between two shut-off valves is about 71,761 cubic meters (2,534,220 cubic feet). However, the amount most likely to be spilled is the oil contained between the two highest elevations on either side of the Wolf River. Consequently, the probable amount of oil to be spilled into the area of break is about 5,600 cubic meters (200,000 cubic feet), and about 2,260 cubic meters of oil is

estimated to infiltrate to the surrounding porous media. The rest of the volume is assumed to be recovered before it can infiltrate. These estimates are based on the actual data collected from the Bemidji spill by the USGS [1].

SECTION 2

LITERATURE REVIEW

2.1 Rupture Potential for Oil Pipelines

There have been a number of studies investigating the hazard and response of buried pipelines to seismic activity. Perhaps the first dealing with the problems in Eastern United States was by Beavers, et.al. who studied the vulnerability of energy systems in the Eastern U.S. [5]. Isenberg, Richardson, and O'Rourke (1989) examined the performance of buried pipes along the San Andreas fault [9]. O'Rourke and Lane (1989) analyzed the liquefaction hazards and their effects on buried pipelines [10]. Finally Hwang and Chen (1990) studied the specific seismic hazard of buried pipelines in the New Madrid zone [11]. The results of these studies indicate that liquefaction would be the most probable cause of buried pipeline rupture, but differential displacement or other mechanisms could also cause a ruptue.

2.2 Monitoring Hydrocarbons in Porous Media

Hydrocarbons from surface spillage and underground storage tank leakage are a widespread source of ground water contamination. The spilled hydrocarbons, which are lighter than water, migrate as light nonaqueous phase liquids (LNAPL) and may accumulate above the water saturation zone. The LNAPL serves as a source of soluble and volatile constituents which can be transported from the contaminated area in the aqueous and gaseous phases [12].

Laboratory experiments have been conducted on sandy soil samples by some researchers to predict the thickness of hydrocarbon (LNAPL) in the porous media. The hydrocarbon thickness in porous media is also called "hydrocarbon volume per unit surface area" or "hydrocarbon specific volume". The hydrocarbon thickness in the porous media (V_o) is estimated by an analytical method described by researchers based on the hydrocarbon thickness that is observed in the monitoring well. In addition, the described analytical method is based on the assumption that the fluids in the porous media are in static (mechanical) equilibrium [13].

Several techniques to predict the soil hydrocarbon thickness from the observed thickness of hydrocarbon in the monitoring well have been proposed by the researchers from experimental observations. The proposed techniques provide only a rough estimation of the soil hydrocarbon thickness.

Van Dam ***et al.*** (1967) proposed that the actual hydrocarbon volume per unit surface area (hydrocarbon specific volume) is less than the LNAPL thickness in monitoring wells [14]. de Pastrovich ***et al.*** (1979) proposed that the measured LNAPL thickness, well product hydrocarbon thickness, in monitoring wells is approximately four times the hydrocarbon thickness in the soil zone [15].

In a laboratory investigation of the relationship between soil and well hydrocarbon thickness conducted by Hall ***et al.*** (1984), he found a one to one ratio of the hydrocarbon thickness in the soil and in the monitoring well [16]. Hampton and Miller (1988) found the techniques proposed by de Pastrovich and Hall to be inadequate for describing their laboratory investigations [17].

A paper by A.M. Farr, R.J. Houghtalen, and D.B. McWhorter (1990) reported that, ". . . there is no simple relation between the soil and well hydrocarbon thickness with general applicability. The ratio of soil hydrocarbon thickness to well hydrocarbon thickness is not, in general, 0.25 (the 4:1 'rule-of-thumb' ratio), nor is the ratio even constant." [12]

A study conducted by R.J. Lenhard and J.C. Parker (1990) related the soil hydrocarbon thickness and the well hydrocarbon thickness by introducing a hydrocarbon reduction factor. The hydrocarbon reduction factor is the ratio of hydrocarbon specific volume in the porous medium to the hydrocarbon thickness in a well. The hydrocarbon reduction factor is estimated based on the Brooks-Corey and van Genuchten models. They concluded that there is no simple linear conversion scheme which can be employed to relate the thickness of hydrocarbon in an observation well to a hydrocarbon volume in porous media. In addition, they revealed that the hydrocarbon reduction factors resulting from the Brooks-Corey and van Genuchten models agree favorably for larger well hydrocarbon thickness but not the smaller well hydrocarbon thickness [12].

2.3 Studies Dealing with the Fate of Hydrocarbons in Aquifers

There have been few studies dealing with the fate of hydrocarbons in aquifers. To the authors' knowledge, the only one in which there was actual data and monitoring of results was written by Hult (1984) who studied a rupture that occurred in Bemidji, Minnesota [1]. About 1600 m^3 of crude oil was released, of which about

1000 m^3 was recovered. The value of this study was in the data collected from an actual oil pipeline rupture. Data were gathered for both the migration and remediation phases of the process.

2.4 Studies Dealing with Modeling Hydrocarbon Flow in Porous Media

The main, if not only, simulation models reported in the literature dealing with two dimensional flow of hydrocarbons were developed by Kaluarachchi and Parker [2]. Both of these models are finite difference; ARMOS [3] deals with horizontal flow and MOFAT deals with vertical flow. MOFAT also has the ability to model dissolution of soluble phases of NAPL [4]. Kaluarachchi and Parker (1989) give the theoretical basis for their models and results of testing them [2].

SECTION 3

BACKGROUND INFORMATION ON THE MODELS

3.1 Description of the ARMOS Model

ARMOS (J.J. Kaluarachchi and J.C. Parker, 1989) is a two-dimensional upstream weighted finite element model and is used to simulate the simultaneous flow of water, air, and NAPL in a porous media (aquifer) [3]. The model is exclusively designed for simulating the areal fluid migration of three phase flow in either one or two horizontal dimensions.

The model adopts an alternative modeling approach involving vertical integration of the governing flow equations under the assumption of near-equilibrium conditions for water and a hydrocarbon in the vertical direction with zero gas pressure gradients. The use of vertically integrated governing equations in this model minimizes the numerical dimensionality and the severe nonlinearity problems. The set of coupled governing equations is solved by adopting upstream weighting functions to improve the computational efficiency.

ARMOS is capable of simulating the migration of separate phase lighter-than-water hydrocarbons in unconfined aquifers under natural gradients following a spill or leakage from the subsurface storage facilities. It can also simulate the recovery of hydrocarbons from trenches or a network of recovery wells to simulate the effectiveness of remediation designs.

Hydrocarbon movement may be simulated with hydrocarbons injected at specified volumetric rates at multiple locations to model hydrocarbon leakage events. Hydraulic recharge is normally stipulated as prescribed volumetric rates at multiple locations during remediation. Multiple water and hydrocarbon recovery wells may be simulated to enable simulation of free product recovery.

Input data for ARMOS include initial conditions prescribed as elevations of air-oil and oil-water fluid elevation interpolated from a set of observation wells, prescribed boundary conditions, soil properties, fluid properties and run-time parameters such as mesh data, time increments and convergence criteria. Boundary conditions are classified as type-1, type-2, or type-3. The Type-1 boundary condition is a constant head condition and stipulates the value of fluid table elevation or pressure head for both water and oil phases. The Type-2 boundary condition is a constant flux condition and stipulates the fluid flux rates for water and oil phases. Well bore air-oil table elevation and oil thickness are required input data at pumping wells only for the free product recovery events. The Type-3 boundary condition is a no-flow boundary. Soil properties in the areal domain can vary spatially and are prescribed as parameters of the Brooks-Corey model. In the absence of detailed information on soil properties, the interactive pre-processor program SOILPROP will provide necessary information on the Brooks-Corey retention parameters based on grain size distribution data. Fluid properties required are viscosity, density and surface tension of the hydrocarbon.

The main output from ARMOS gives predicted fluid table elevations, oil volume per unit area (V_o), cumulative recovery of water and hydrocarbon from wells, pumping rates of water and hydrocarbon, and the total volume of water and hydrocarbon in the domain at prescribed time intervals. In addition, for calibration with observation well data, fluid table elevation and oil volume per area can be obtained at user selected locations.

3.2 Description of the MOFAT Model

MOFAT (J.J. Kaluarachchi and J.C. Parker, 1989) is a two-dimensional upstream weighted finite element model and is used to simulate the simultaneous flow of water and NAPL in a three fluid phase porous medium with transport of partitionable organic components [4]. The model is exclusively used for simulating fluid movement in vertical porous media. In this model, the gas phase gradients are assumed to be negligible. Nonlinear analysis of the finite element formulation utilizes either the Picard or Newton Raphson scheme. The initial conditions are specified as pressure head values for both water and oil phases with the option of stipulating 'no-oil' condition in the flow analysis. The model allows one of two boundary conditions for flow analysis. The Type-1 boundary condition (like that of ARMOS) is a constant head condition and requires pressure head values for water and oil phases. The Type-2 boundary condition is constant flux and requires the fluid flux rates for water and oil phases. The main flow module is coupled with the transport module to predict transport of up to five partitionable organic components

using the local equilibrium assumption. The transport analysis of the partitionable components includes the initial boundary condition, type-1, and type-3 boundary conditions (explained later). The initial condition is used to stipulate the value of an equivalent water phase concentration of each component using the local equilibrium. The Type-1 boundary is used to allow the partitionable components in the gas phase to diffuse into the atmosphere through the evaporative boundaries. The Type-3 boundary condition is employed by stipulating the value of equivalent water phase in inflowing oil phase under the local equilibrium. The contaminants are allowed to enter the system through the oil phase.

Input data for flow analysis include soil hydraulic properties, fluid properties, mesh data, and run-time parameters. Soil hydraulic properties can be stipulated using either van Genuchten or Brooks-Corey model and the media can be heterogeneous with up to ten soil types. Fluid properties are scaling parameters, density, and viscosity.

Input data for transport analysis includes transport parameters and fluid properties of each partitionable component. Required transport parameters for each partitionable component are diffusion coefficient, longitudinal and transverse dispersivities, equilibrium partition coefficients, and first order rate terms (if any). Fluid properties required of each component are density and molecular weights.

The main output from MOFAT gives saturations and velocities at each node at user specified intervals, total volumes of water and oil together with net changes, run-time information on convergence, time steps and number of iterations. In

addition, it also provides the concentrations of each component in the water, oil, gas, and solid phases as well as the total mass of each component in each phase.

3.3 Governing Equations for Multiphase Flow

Generalized Darcy equation is given by [18]:

$$q_{ip} = -k_{rp} K_{spij} \left[\frac{dh_p}{dx_j} + \rho_{rp} e_j \right] \tag{3.1a}$$

in which

$$K_{spij} = \frac{k_{ipj} \rho^* g}{\eta_p} \tag{3.1b}$$

$$\rho_{rp} = \frac{\rho_p}{\rho^*} \tag{3.1c}$$

$$h_p = \frac{p_p}{\rho^* g} \tag{3.1d}$$

where i and j are direction indices (i, j = 1,2,3),

q_{pi} = Darcy velocity of fluid phase p in direction i

k_{ij} = Intrinsic permeability tensor of the porous medium.

k_{rp} = Relative permeability to phase p.

η_p = Absolute viscosity of phase p.

ρ_p = Density of phase p.

g = Gravitational acceleration.

e = dz/dx_j

K_{spij} = Saturated conductivity of phase p for directions i and j.

h_p = Fluid pressure head.

ρ_{rp} = Ratio of the in situ fluid density to that of a reference fluid of density ρ^*.

For an incompressible porous medium, the fluid phase continuity relations are of the form

$$\Phi \frac{d\rho_p S_p}{dt} = -\frac{d\rho_p q_{pi}}{dx_i} + \gamma_p \qquad (3.2)$$

Substituting Darcy's equation for q_p yields,

$$\Phi \frac{d\rho_p S_p}{dt} = \frac{d}{dx_i} K_{pij} \left[\frac{dh_p}{dx_j} + \rho_{rp} e_j \right] + \gamma_p \qquad (3.3)$$

For a three fluid phase porous medium system with water, organic liquids and air, each equation may be written for each phase (p = w, o, a) from the above equation.

3.4 Mass Flux Equations

Convective mass transport equation is given by

$$J_{\alpha pi}^{con} = c_{\alpha p}\, q_{pi} \tag{3.4}$$

where,

$J_{\alpha pi}^{con}$ = Convective mass flux density of constituent

α in phase p in the i-direction.

$c_{\alpha p}$ = Concentration of α in the phase p.

The modified diffusive mass transport equation for the porous medium is given by:

$$J_{\alpha pi}^{diff} = -\Phi\, S_p\, D_{\alpha p}^{diff} \frac{dc_{\alpha p}}{dx_i} \tag{3.5}$$

where,

$J_{\alpha pi}^{diff}$ = Diffusive mass flux density of species

α in phase p in the i-direction.

$D_{\alpha p}^{diff}$ = Effective diffusion coefficient.

The process of mechanical dispersion may under certain constraints obey a diffusion type equation commonly written in the form

$$J_{\alpha pi}^{hyd} = -\Phi S_p D_{pij}^{hyd} \frac{dc_{\alpha p}}{dx_j} \tag{3.6}$$

where,

$J_{\alpha pi}^{hyd}$ = Dispersive mass flux density of α in

the phase p in the i-direction.

D_{pij}^{hyd} = Dispersive tensor in the p-phase.

3.5 Continuity Equations for Transport

If there is no chemical transformations of component α within the p-phase, mass conservation of species α in the phase p requires that

$$\Phi \frac{dc_{\alpha p}}{dt} + \frac{dJ_{\alpha pi}}{dx_i} - R_{\alpha p} = 0 \qquad (3.7)$$

where,

$R_{\alpha p}$ = Net mass transfer rate per porous medium volume

of species α into (+) or out of (-) the p-phase. $J_{\alpha pi}$ = Total mass flux density of component α in p-phase.

The desired form of the transport equation is given by

$$\Phi S_p \frac{dc_{\alpha p}}{dt} + q^x \frac{dc_{\alpha p}}{dx_i} - \frac{d}{dx_i}\left[\Phi S_p D_{\alpha pij} \frac{dc_{\alpha p}}{dx_j}\right] - R_{\alpha p} + \frac{c_{\alpha p}\gamma}{\rho_p} = 0 \qquad (3.8)$$

where,

γ_p = Total phase mass transfer rate.

The total phase mass transfer rate is related to the component mass transfer rates by

$$\gamma_p = \sum_{\alpha} R_{\alpha p} \tag{3.9}$$

For three fluid phase system, three equations may be written for the water phase, the organic liquid phase, and the gas phase by replacing p by w, o and a from the above equation.

SECTION 4

DATA ACQUISITION AND DISCUSSION

The objective of this section is to provide an overview on data acquisition and a summary of the required input parameters to the models.

4.1 Crude Oil Properties

In this study, a light crude was assumed to be spilled from a pipeline rupture because it has low density and viscosity as compared to the heavy crude; consequently, it migrates and penetrates the porous media more readily than the heavy crude. Over the past few years, types of light crude which were commonly supplied in the pipeline 22 are given in table 4.1 [19]. EIC, LLS, LMS, and MCC are Eugene Island Crude, Light Louisiana Sweet, Louisiana Mississippi Sweet and Mississippi Canyon Crude respectively. Among those light crude, EIC was selected as representative of all light crudes because its properties approximate the average of the other light crudes.

The physical properties of the crude were taken from the CAPLINE CRUDE ASSAYS LISTING 1990 produced by the SHELL PIPE LINE CORPORATION. The light crude properties listed in Table 4.I were measured at 15.6 degree Centigrade (60 degree Fahrenheit). The absolute viscosity of EIC was measured in the Standard Saybolt Unit. The corresponded value of the absolute viscosity of EIC was 8.06 centipoise and the kinematic viscosity was 9.40 centistoke [20].

Table 4.I Crude types and their properties

Crude Type	Gravity API at 15.6 deg. C (60 deg. F)	Vapor Pressure at 100 F	Sulphur	Pour Point %	Pour Point F	Viscosity (SSU) at 15.6 deg. C (60 deg. F)
EIC	33.6	5.5	0.80		-24	58.7
LLS	35.0	4.2	0.40		-24	53.6
LMS	40.2	0.8	0.10		-30	47.5
MCC	42.4	3.5	0.07		+3	38.2

Source: Shell Pipe Line Corporation

A sample of the EIC was furnished by the MAPCO PETROLEUM CORPORATION. Laboratory analysis was carried out on the sample to measure the mass fraction of each of the monoaromatic hydrocarbon compounds and their solubilities, in order to compute their equilibrium partition coefficients. The monoaromatic compounds were benzene, toluene, ethylbenzene and xylene. The laboratory analysis was done by the Core Laboratory Method in the Core Laboratories [21]. The results of the analysis are given in Table 4.II. Moreover, among the xylene components listed in Table 4.II, only ortho-xylene was adopted for the simulation because it was the only component for which the relevant information could be found from the literature.

Table 4.II Results of laboratory analysis on the mass fraction of BTEX components

Partition of Aromatics: Crude oil/water at 70 deg. F Analysis of equal volumes of water & oil: 10 ml for both phases

Component	% w.t in oil	ppm w.t in water phase
Benzene	0.14	8
Toluene	0.51	44
Ethylbenzene	0.15	5
Meta-xylene	0.40	14
Para-xylene	0.19	5
Ortho-xylene	0.30	8

Component	w.t in oil (gm) 10^{-2}	% w.t in water (gm) 10^{-4}	w.t in oil (gm) 10^{-3}	Conc. in oil (gm/cm^3) 10_{-3}	Equilib. in water (gm/cm^3) 10^{-4}	Partition Coeff.
Benzene	1.2250	8.0	8.0	1.2250	8.0	1.53125
Toluene	4.4625	44.0	44.0	4.4625	44.0	1.01420
Ethyl-Benzene	1.3125	5.0	5.0	1.3125	5.0	2.62500
Xylene:						
Meta	4.1125	14.0	14.0	4.1125	14.0	2.93750
Para	1.6625	5.0	5.0	1.6625	5.0	3.32500
Ortho	2.6250	8.0	8.0	2.6250	8.0	3.28125

w.t - weight
Conc. - Concentration
Equilib. - Equilibrium
Coeff. - Coefficient

4.2 Soil Properties

The soil properties required for the models were primarily the porosity and the grain size distribution. The porosity used in the simulations was estimated from field samples to be 0.35. A mean grain size distribution was adopted from numerous analysis of Memphis Sand samples. The adopted grain size distribution was similar to that reported in the article by Parker ***et al.*** (1988), in the Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water [22].

The available grain size distribution constituted about 97.6 percent of sand fraction of the total soil particles. The grain size distribution and the type of soil composition are listed in the Tables 4.III and 4.IV respectively.

Table 4.III Mean grain size distribution

Grain Diameter (mm)	Mass In Fraction %
< 0.074	1.6
0.074 - 0.149	3.8
0.149 - 0.250	40.5
0.250 - 0.420	38.0
0.420 - 0.840	13.7
0.840 - 2.000	1.2
2.000 - 4.760	0.4
4.760 - 8.000	0.8

Table 4.IV Percent of composition of soil

Type of soil	% mass in size fraction
Fine silt & clay	1.6
Fine sand	82.3
Medium sand	14.9
Coarse sand	0.4
Gravel	0.8

The grain size distribution was used to estimate the Brooks-Corey retention function by inputing it into the interactive program SOILPROP described by Mishra ***et al.*** (1988) [23, 24]. In this study, SOILPROP was also utilized to predict the horizontal and vertical hydraulic conductivities. The calculated Brooks-Corey parameters for the ARMOS and MOFAT models were different, and they were used separately for the simulations. The predicted Brooks-Corey values and their uncertainties for both models are listed in the Tables 4.V and 4.VI. h_d, λ, and S_{min} are air entry head, Brooks-Corey constant, and residual saturation. A summary of the input parameters of soil and fluid properties for both models are given in Tables 4.VII and 4.VIII. In accordance to most of the literature, the horizontal hydraulic conductivity is significantly larger than the vertical hydraulic conductivity. By using SOILPROP, the predicted horizontal and vertical saturated conductivities were 54.308 and 2.263 meters per day respectively. That is, the ratio of the horizontal conductivity to the vertical conductivity was about 24.

Table 4.V Brooks-Corey retention parameters and their uncertainties for ARMOS Simulation

Parameters	Estimated Values	Standard Deviation
h_d (m)	0.054	0.010
λ	0.552	0.161
S_{min}	0.642	0.000
K_{sat} (m/d)	54.308	107.170

Parameter correlation matrix

	h_d	λ
h_d	.100E+01	
λ	.239E-01	.100E+01

For log-normal fit, $R^2 = 0.8852$
For Van Genutchen model fit, $R^2 = 0.9531$

The β_{ao} and β_{ow} are unrefined petroleum hydrocarbons scaling factors. They were estimated by using the correlation between the oil surface tension and the oil specific gravity suggested by Baker and Swerdloff (1956) [25, 26]. The steps of the computation are outlined in Appendix A.

Table 4.VI Brooks-Corey Retention Parameters and their Uncertainties for MOFAT

Parameters	Estimated Values	Standard Deviation
h_d (m)	0.334	0.251
λ	0.787	0.262
S_{min}	0.003	0.016
K_{sat} (m/d)	2.263	4.466

Parameter correlation matrix

	h_d	λ	S_{min}
h_d	.100E+01		
λ	.978	.100E+01	
S_{min}	.274E-01	.160	.100E+01

For log-normal fit, $R^2 = 0.8852$
For Van Genutchen model fit, $R^2 = 0.9892$

Table 4.VII A summary of input parameters of soil and fluid properties for ARMOS

Parameters	Values
Φ	0.350
λ	0.552
Sm	0.642
hd (m)	0.054
Kswx (m/day)	54.308
Kswy (m/day)	54.308
ρro	0.857
ηro	7.180
βao	2.400
βow	1.720

Table 4.VIII A summary of input parameters of soil and fluid properties for MOFAT Simulation

Parameters	Values
Φ	0.350
λ	0.787
Sm	0.003
hd (m)	0.334
Kswz (m/day)	2.263
Kswx (m/day)	54.308
ρro	0.857
ηro	7.180
βao	2.400
βow	1.720
εL	0.400
εT	0.050

The ε_L and ε_T, longitudinal and transverse dispersivities, were porous medium constants. According to Parker (1989):

> "Longitudinal dispersivities typically are found to range from 0.01 to 0.1 of the mean travel distance for distances less than 1 km and diminish to somewhat smaller fractions of travel distance beyond this (Gelhar, 1986)." [27, 28]

Transverse dispersivity is typically in the range of 0.1 to 0.3 times the longitudinal dispersivity [29, 30] ε_L and ε_T were assumed as 0.4 meters and 0.05 meters for the modeling purposes. Based on these values, the longitudinal dispersivity was about 10 times larger than the transverse dispersivity.

4.3 Properties of BTEX for the Transport Simulation

For the organic transport simulation, each of the monoaromatic components was required to have the values of the $\Gamma_{\alpha o}$, $\Gamma_{\alpha a}$, ρ_α, M_α, and $D^\circ_{\alpha w}$ for input. The respective values for each component are listed in Table 4.IX.

Table 4.IX Properties of organic components for MOFAT Simulation

Parameters	Benzene	Toluene	o-Xylene	Ethlybenzene
$\Gamma_{\alpha o}$	1.5313	1.0142	3.3250	2.6250
$\Gamma_{\alpha a}$	0.2400	0.2800	0.2200	0.3700
ρ_α	879.0000	867.0000	861.0000	867.0000
M_α (kg/mole)	0.0780	0.0920	0.1060	0.1060
$D^\circ_{\alpha w}$ (m^2/day)	0.000090	0.000090	0.000090	0.000090

$\Gamma_{\alpha o}$ is equilibrium partition coefficient and was estimated based on the results obtained from the CORE LABORATORIES. $\Gamma_{\alpha a}$ is the nondimensional Henry's law constant and was obtained by referring to the values measured by Lyman ***et al.*** (1982) [31]. The diffusion coefficient of the components, $D^{\circ}_{\alpha w}$, was taken from the article by Parker ***et al.*** (1989),in the Proceedings of the International Conference on Groundwater Contamination [32, 33]. The value of $D^{\circ}_{\alpha w}$ was approximately 0.000090 square meters per day and was assumed equal for all the components. Finally, ρ_{α}, and M_{α} are density and molecular weight of the organic component. These values were obtained from the measured values by Riddick and Bunger (1970) [34].

4.4 Hydrology of the Study Area

The predicted average ground water tables were based on the data collected from the USGS for the Shelby County Area. The Geological Information System (GIS) software package was used to develop the average water tables in the study area by projecting the available data in the Shelby County. However, a visit to the site resulted in modifying the predicted ground water table. Recall, the pipeline is buried about 1.22 meters (4 feet) below the ground surface. The water table under the pipe was assumed to be 2.7 meters below the ground surface. The slope of the water table was 0.0052. A 10 meter depth of unconfined aquifer, 250 meters length and 200 meters width were used to construct the grids.

SECTION 5

MODELING APPROACH

This section describes the procedures of estimating the probable released oil volume from the ruptured pipeline and the application of the models to the ruptured pipeline scenario.

5.1 Procedure for Estimation of Released Spill

In applying the ARMOS model, the probable volume of released oil for the ruptured pipeline is required in order to predict the extent of oil dispersion in the subsurface.

The probable volume of oil from a break is estimated by calculating the volume in pipeline between the two surrounding high elevations, and then by subtracting the oil that would collect in the valleys between the ridges, see Figure 1-2. The estimated released volume is about 5,600 cubic meters (200,000 cubic feet).

From an accidental pipeline break that occurred on August 20, 1979 near Bemidji, Minnesota, about 40 percent of the spill infiltrated into the subsurface and 60 percent of the spill was recovered by surface pumping [1]. Therefore, for the ARMOS simulation, only 40 percent of the total spill of 5,600 cubic meters is assumed to be infiltrated into the subsurface. The assumed infiltrating volume is approximately 2,260 cubic meters (80,000 cubic feet).

5.2 Procedure for Areal Simulation (ARMOS)

The goal of the application of this model is to predict the crude oil dispersion horizontally above the water table after 10 days as well as to evaluate the extent of further dispersion of oil for periods after 30 and 60 days.

A geometric domain of 250 meters long by 200 meters wide was selected for constructing the grid elements of an unconfined aquifer, refer to Figure 5-1. The effective depth of the aquifer was assumed to be constant at 10 meters from the ground surface. The modified water levels were fixed at 7.3 meters and 6.0 meters on the sections AB and CD respectively from the bottom of the aquifer. Hydraulic properties of the aquifer and soil were assumed to be homogeneous with parameters representative of a well graded sandy material and fluid properties typical for crude oil. A summary of the soil and fluid properties required for this simulation was previously given in Table 4.7.

In simulating the oil infiltration event in an initially oil free medium, the use of H_o value of zero is not recommended because it will cause numerical instability due to the presence of air-entry pressure head terms of the Brooks-Corey model. H_o is the stipulated thickness of oil in the monitoring well. However, the use of an H^{min} value of 0.1944 meters is estimated by the method described by Parker ***et al.*** [22]. If the oil height H_o falls below this value, the volume of oil per area (V_o) will be zero. The estimation of H^{min} value is outlined in Appendix A.

In the infiltration simulation, oil is introduced into the subsurface by imposing 41 prescribed volumetric source-sink nodes which are illustrated in Figure 5-1. The boundary condition for these source-sink nodes are accomplished by stipulating the rate of the infiltrating oil volume. However, the rate imposed through these nodes are adjusted by trial and error in order to maintain an approximate value of 2,260 cubic meters for three different periods of 10, 30, and 60 days.

5.3 Procedure for Estimation of the Volume of Crude in Vertical Domain

The estimation of the volume of crude oil for the two-dimensional vertical domain simulation was estimated by assuming that the water table and the volume of oil per area in the porous medium were level and linear. The values of the volume of oil per area (V_o) were estimated by referring to the simulated results of 10 days infiltration from ARMOS simulation. The estimation yielded a volume of 32 cubic meters per meter by summing values of V_o along a distance of 135 meters above the water table. The procedures of the estimation are outlined in Appendix A.

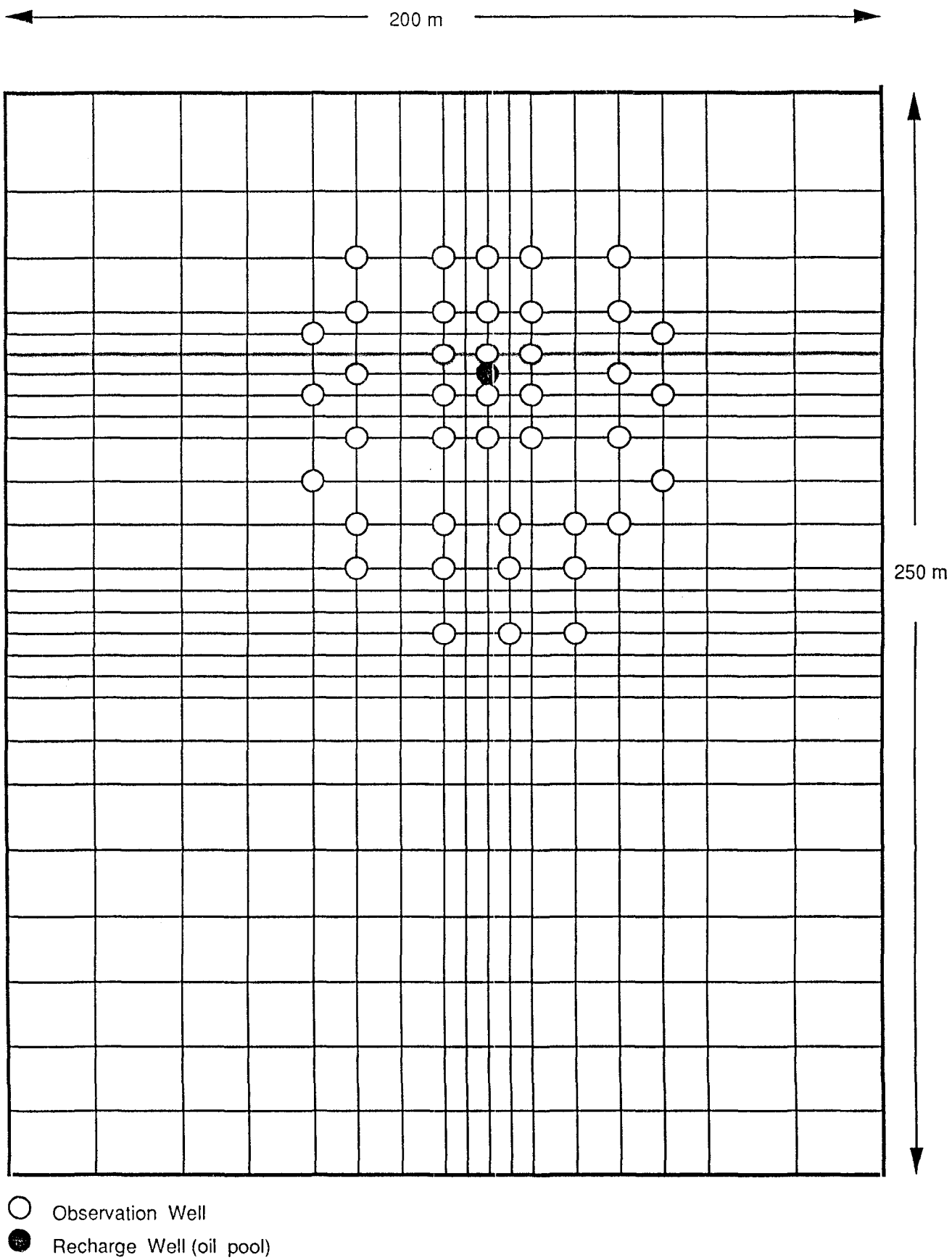

Figure 5-1 Horizontal Domain of the Unconfined Aquifer

5.4 Procedure for Vertical Simulation (MOFAT)

The application of this model was used to predict the physical transport of the monoaromatic components of the estimated released volume of oil to a buried pipeline scenario. The domain used for this simulation was a vertical slice of 10 meters deep by 250 meters long through the vadose and groundwater zones with the spill source located in the unsaturated zone, see Figure 5-2. The soil no. 1 as illustrated in the domain was 1.22 meters deep by 10 meters long and represented the area which has a very coarse media with an assumed value of porosity of 0.7. Both vertical and horizontal hydraulic conductivities applied to this zone were 54.3080 meters per day resulting from the pool of oil after the pipeline rupture. The contaminants were infiltrated through the vadose zone from the ruptured point located at 1.22 meter below the ground surface, to the ground water system. The rest of domain was represented as soil no. 2 which has a porosity of 0.35.

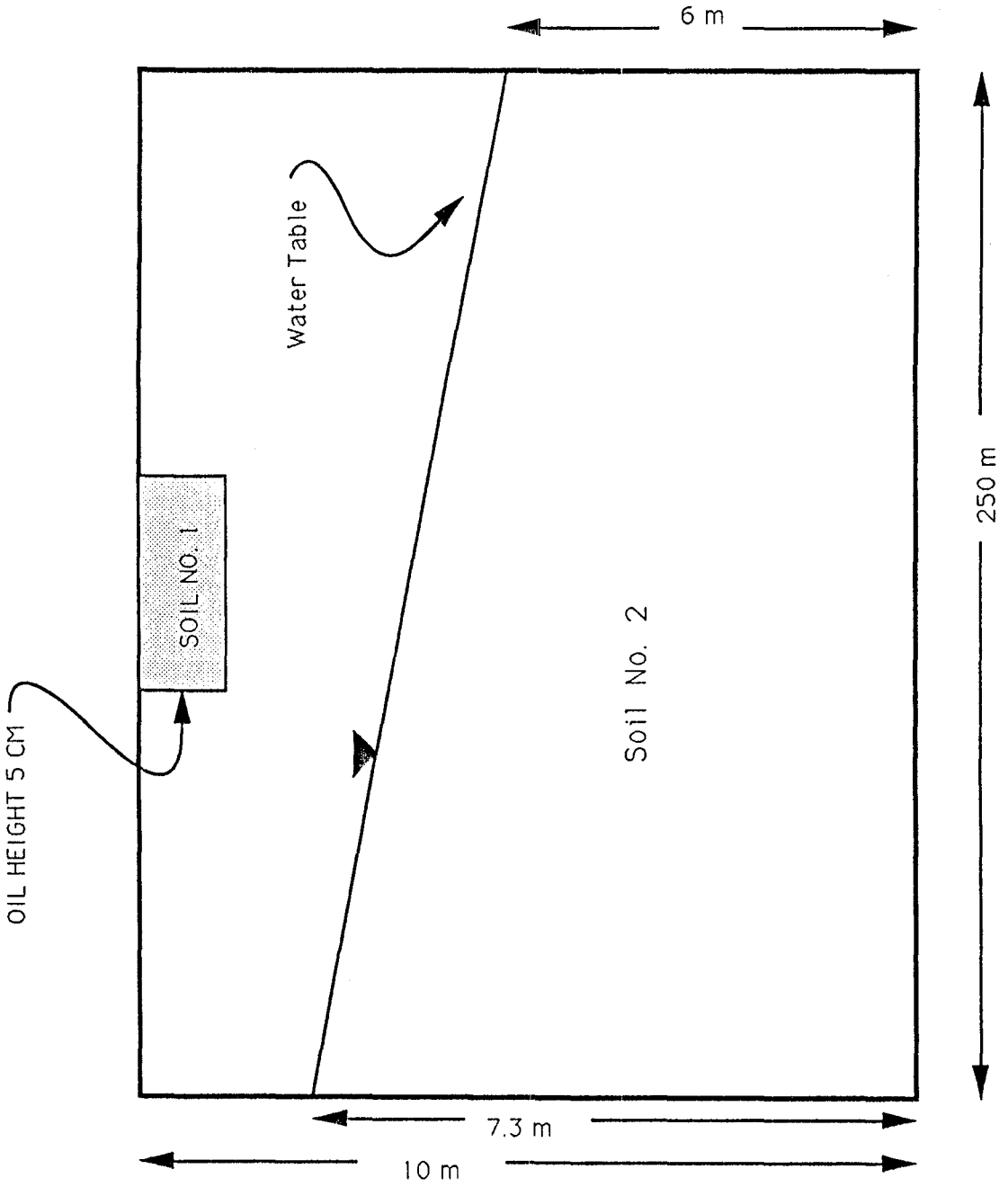

Figure 5-2 Vertical Domain of the Unconfined Aquifer

In the infiltration simulation, the initial distribution of water pressure was in vertical equilibrium, with a water table having a constant slope of 0.0052, and the system initially free of oil. The water surface along the water saturated portion of the right and left boundaries were maintained at 7.3 and 6.0 meters respectively.

For the flow analysis, a zero water flux was imposed across the bottom of the aquifer and vadose zone boundaries. Oil was allowed to infiltrate along a 10 meter segment of the upper surface under an assumed water equivalent head of 5 cm and thereafter was maintained at zero flux. Crude oil containing of 0.14, 0.51, 0.15, and 0.30 percent of benzene, toluene, ethlybenzene, and oxylene respectively were used in this simulation. For the water phase, a 10 meter segment of the upper surface remained at zero flux at all times. A type-1 boundary condition was used to stipulate the water head that corresponds to the initial values of 7.3 and 6.0 meters. A type-2 boundary condition was used to stipulate a zero-flux for the oil phase.

For the transport analysis, the water phase concentration of the benzene, toluene, ethlybenzene, and oxylene are assumed to be 0.8, 4.4, 0.5, 0.8 kg per cubic meters, for type-3 boundary condition in the immiscible (oil) phase during oil infiltration and zero during redistribution. The type-3 boundary condition was used to stipulate the value of equivalent water phase concentration in inflowing oil phase using the local equilibrium. For the remaining boundaries, a zero dispersive flux condition was assumed during the entire simulation.

The infiltration was simulated for 10 days to accommodate the prescribed oil volume of 32 cubic meter per meter in the system. The redistribution is then simulated for 30, 60, 90, and 120 days. The soil and fluid properties are given in Table 4.8 and the transport parameters are given in Table 4.9.

SECTION 6

RESULTS AND DISCUSSIONS

6.1 Results from the ARMOS Simulation

The extent of the spilled crude migration for the specified duration was predicted by the application of ARMOS model. The predicted plume's migrations for the periods of 2, 10, 30, and 60 days by the ARMOS simulation are shown in Figures 6-1, 6-1, 6-3, and 6-4. These Figures show the plume migrating horizontally and laterally on the water table. Figures were produced by using GRAPHER/SURFER software [35]. In addition, the overview of the oil migration at the probable spilled site is shown in Figure 6-5.

By the end of two days, the plume covered an area of approximately 8,500 square meters with the maximum height of oil of 1.20 meters in the soil. At the end of 10 days, the plume covered an area of approximately 10,800 square meters with the maximum height of oil of 0.42 meters. Similarly, at the end of 30 days, the plume covered an area of 18,800 square meters with the height of oil of only 0.24 meters. From that point on, there was very little spreading because there was not enough hydraulic gradient to drive the viscous crude oil.

From the simulated results, it can be concluded that the infiltrated volume of crude oil of 2,260 cubic meters after a pipeline rupture would cover an approximate area of 10,800 square meters for the period of 10 days. With the unchanged volume of oil, the plume would likely cover the maximum area of

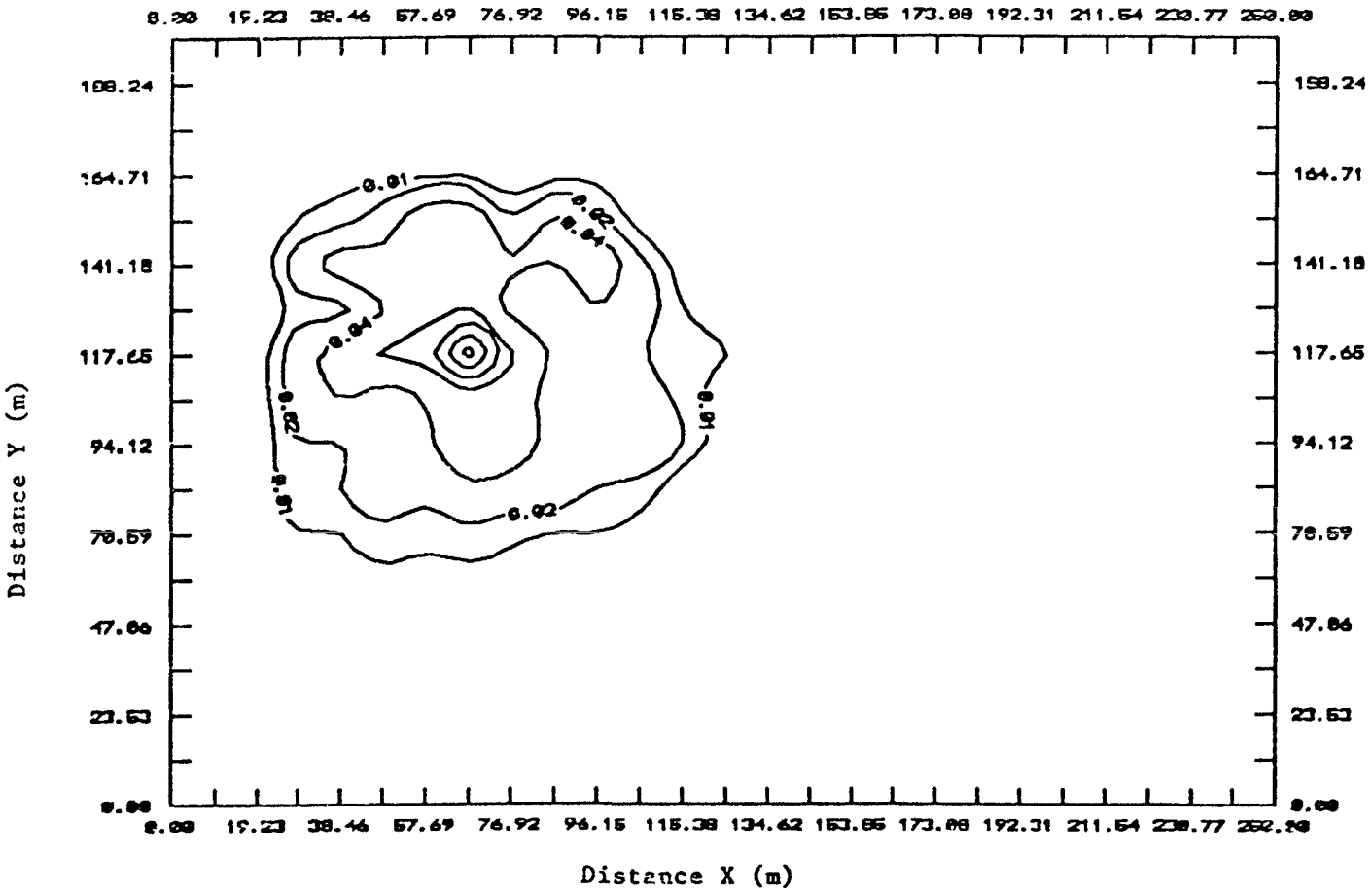

Figure 6-1 Migration of EIC Oil After 2 Days Infiltration

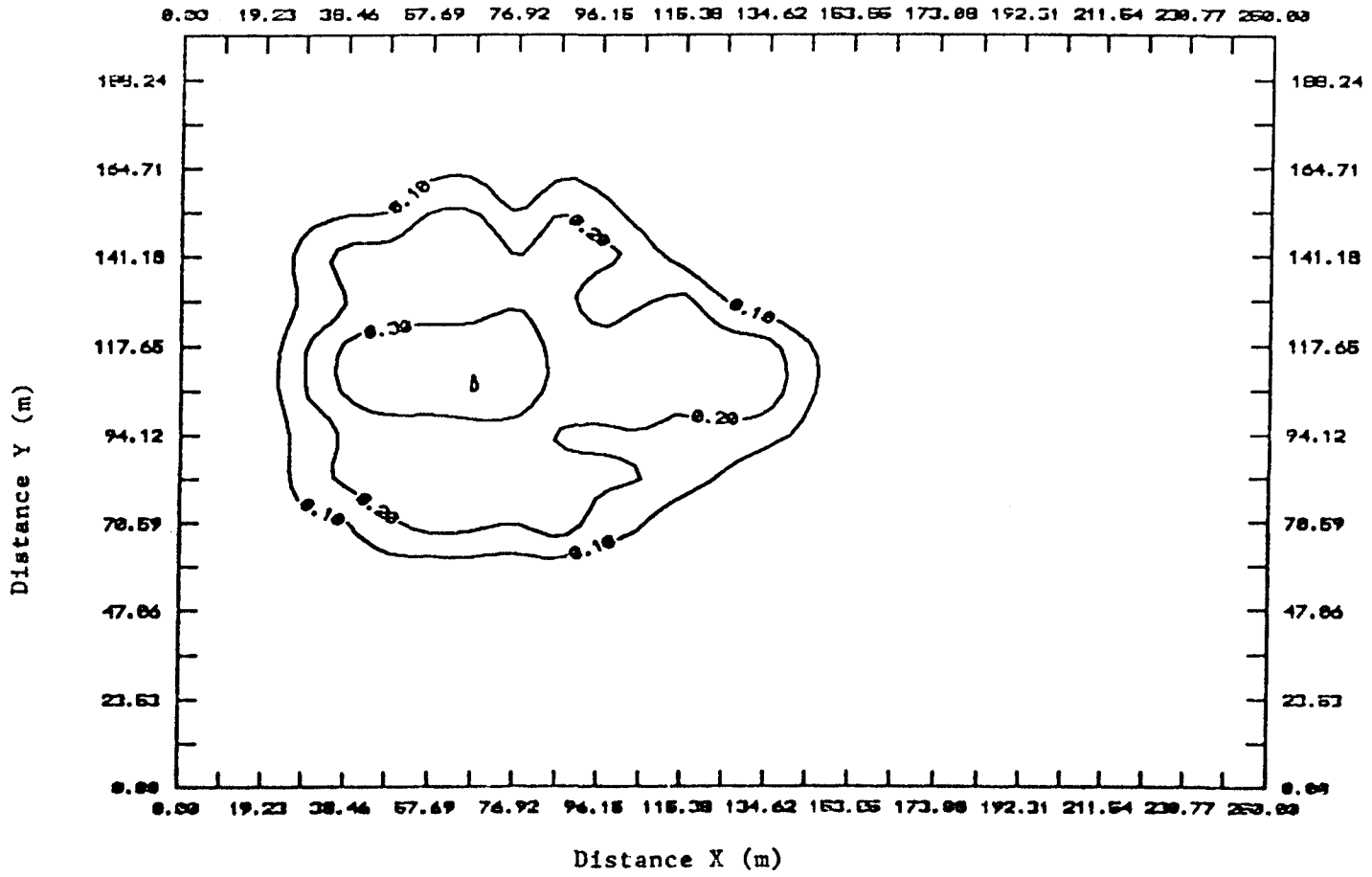

Figure 6-2 Migration of EIC Oil After 10 Days Infiltration

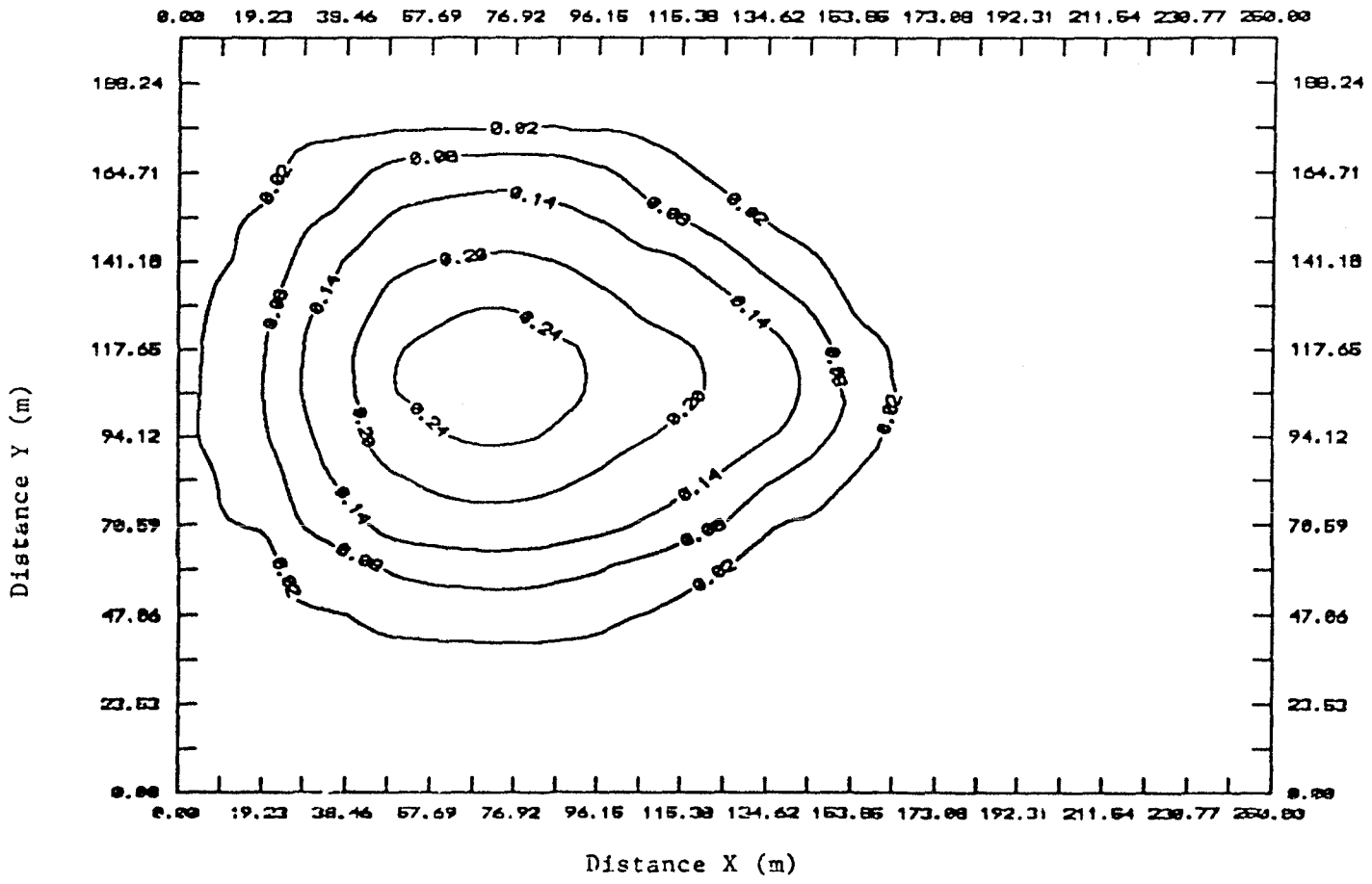

Figure 6-3 Migration of EIC Oil After 30 Days Infiltration

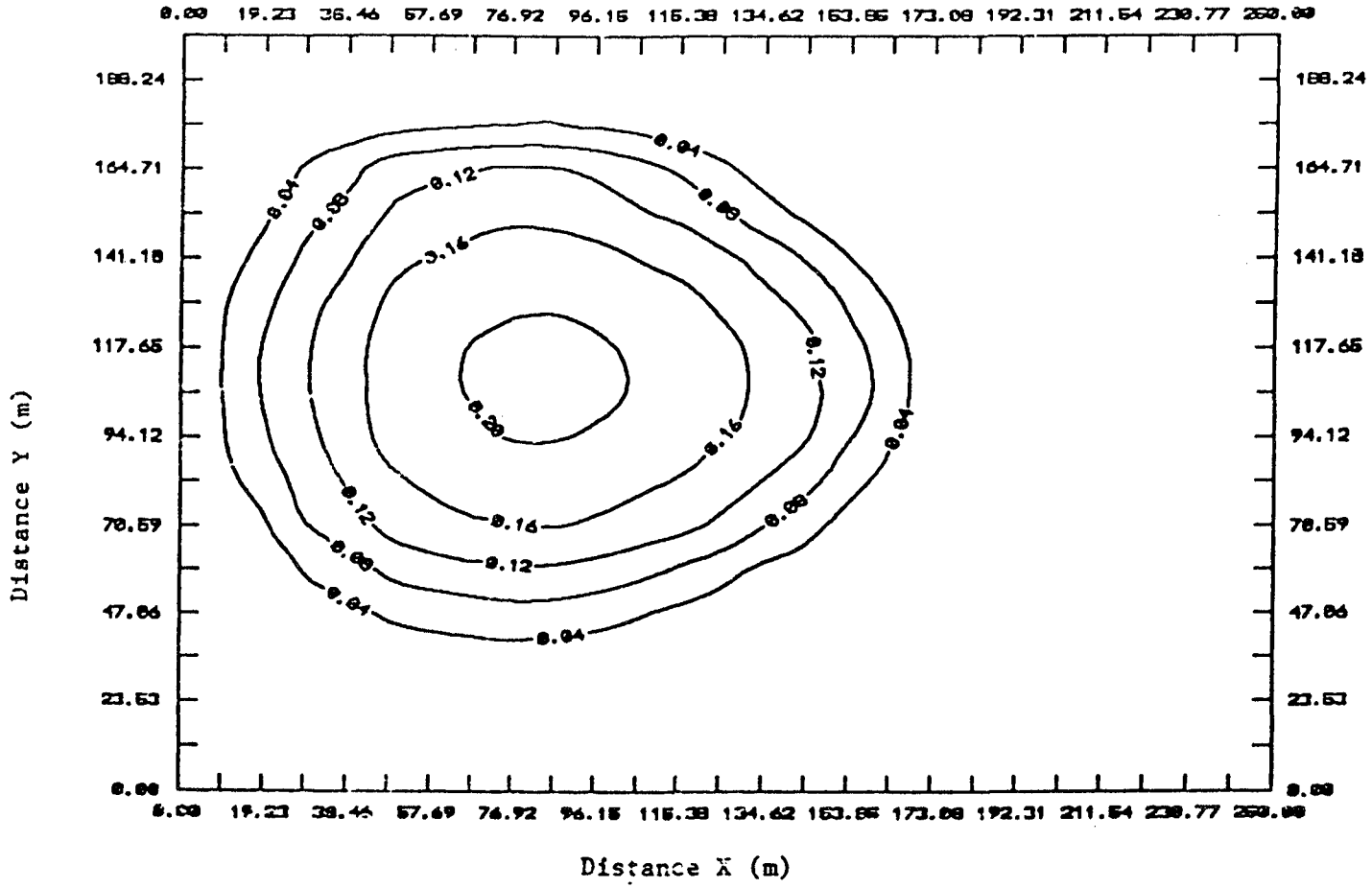

Figure 6-4 Migration of EIC Oil After 60 Days Infiltration

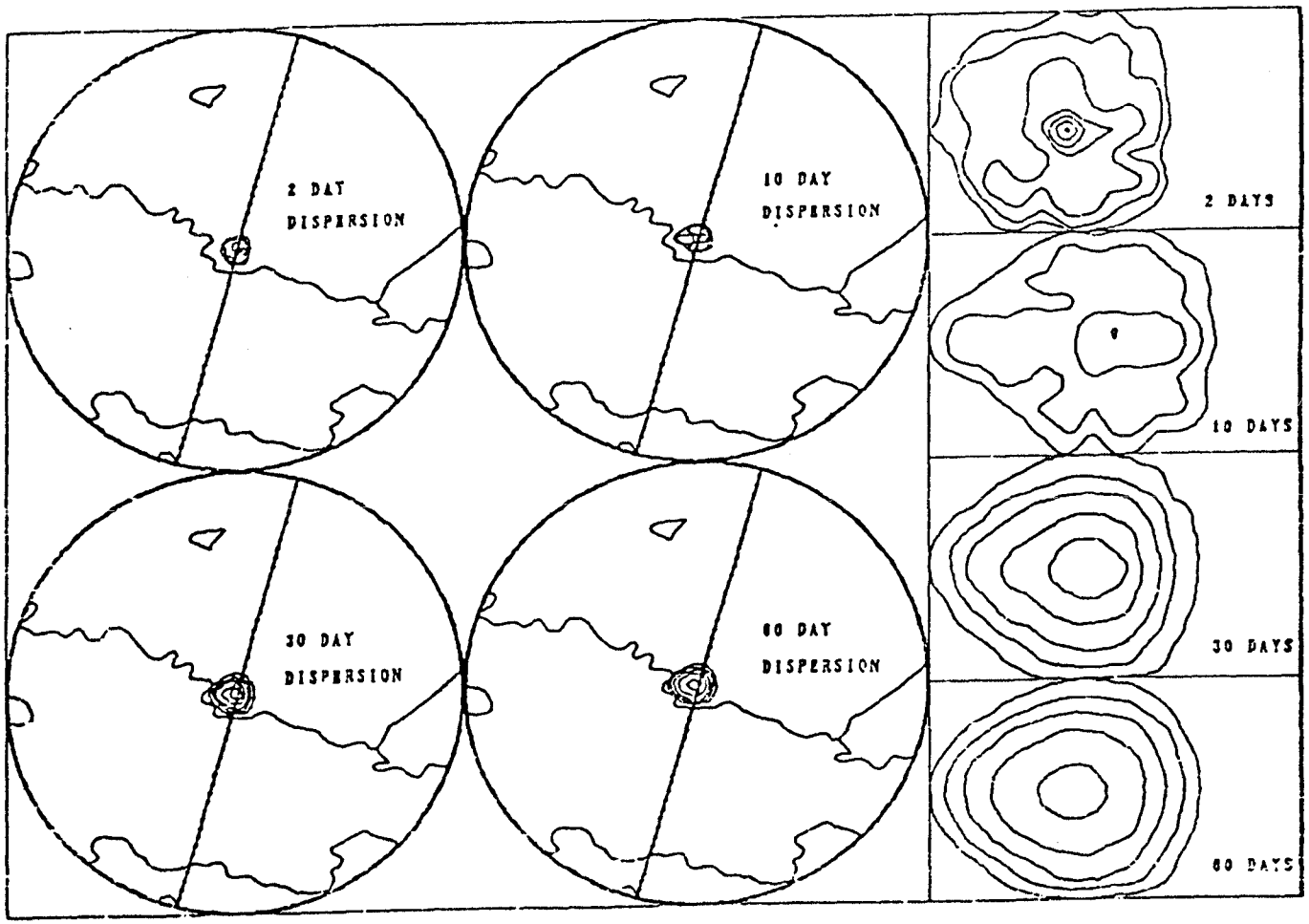

Figure 6-5 Overview of EIC Oil Migration

18,800 square meter at the end of 30 days. Therefore, the incremental coverage between the duration of 10 days and 30 days was approximately 8,000 square meters and there is no significant spreading beyond the period of 30 days.

6.2 Results from the MOFAT Simulation

Migration of oil plume by MOFAT model was represented in the form of oil saturation. Predicted oil saturations over different durations are shown in Figures 6-6 through 6-10. After 120 days of redistribution (i.e., at the end of 130 days), oil plume migration virtually ceased due to the low relative permeability associated with diminishing fluid saturation. Due to the high viscosity and low density ratios of the oil mixture, the oil plume penetrated about 3.20 meters below the original air-water table as it spread laterally along the hydraulic gradient. During this period, the highest oil saturation was 0.60 and this occurred in a region located under the original spill site.

Predicted water phase concentrations of BTEX's are shown in Figures 6-11 through 6-30. The plots indicate that the pattern of the aqueous phase concentrations for BTEX's at a specific duration are similar. However, the aqueous phase concentrations for Toluene are greater than the rest of the components. (Refer to Figures 6-15 through 6-20). As it is the most soluble component, it disperses with a phase concentration of 0.20 kilogram per cubic meter at distances of 56, 79, 102, and 130 meters away from spill site over the periods of 30, 60, 90, and 120 days of redistribution. The results indicated that,

although the oil plume itself does not move far from the spill site, the dissolution results in a growing aqueous phase plume migrating in the direction of groundwater flow.

The amount of BTEX's dissolved into the ground water during the period of redistribution is shown in the Figure 6-31. The predicted cumulative masses of BTEX's are somewhat higher than actual for the period after 60 days due to numerical error accumulation of mass transfer rates between phases during long term transient flow condition. The predicted total amount of BTEX's dissolved in the ground water over the periods of 30, 60, 90, and 120 days of redistribution are 176, 276, 325, and 358 kilograms respectively. Recall that the EPA standard for benzene in drinking water is 0.005 milligram per liter. Assuming a similar standard for the other BTEX's, it would take about 70 millions cubic meters of water to dilute the 350 kilogram of BTEX's down to the EPA standard. Assuming a porosity of 0.35 in the Memphis Sands, this would be over a square kilometer of aquifer contamination even if the BTEX's were perfectly distributed over the area. Clearly, prompt remediation procedures are required. Unfortunately, recent results have shown that attempts to pump contaminants from porous media have not always been successful; however, if a combination of practices are used a disaster to Memphis Sands may be averted.

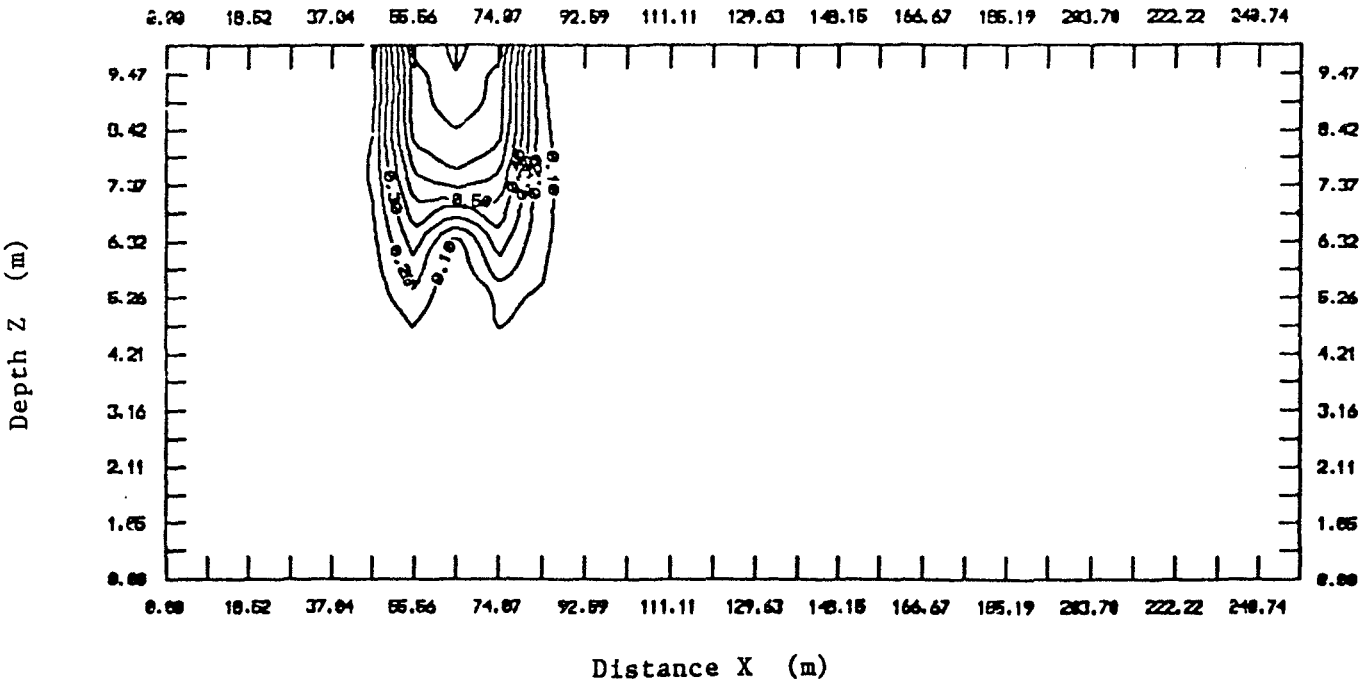

FIGURE 6-6 Saturation of EIC oil at the end of 10 days infiltration

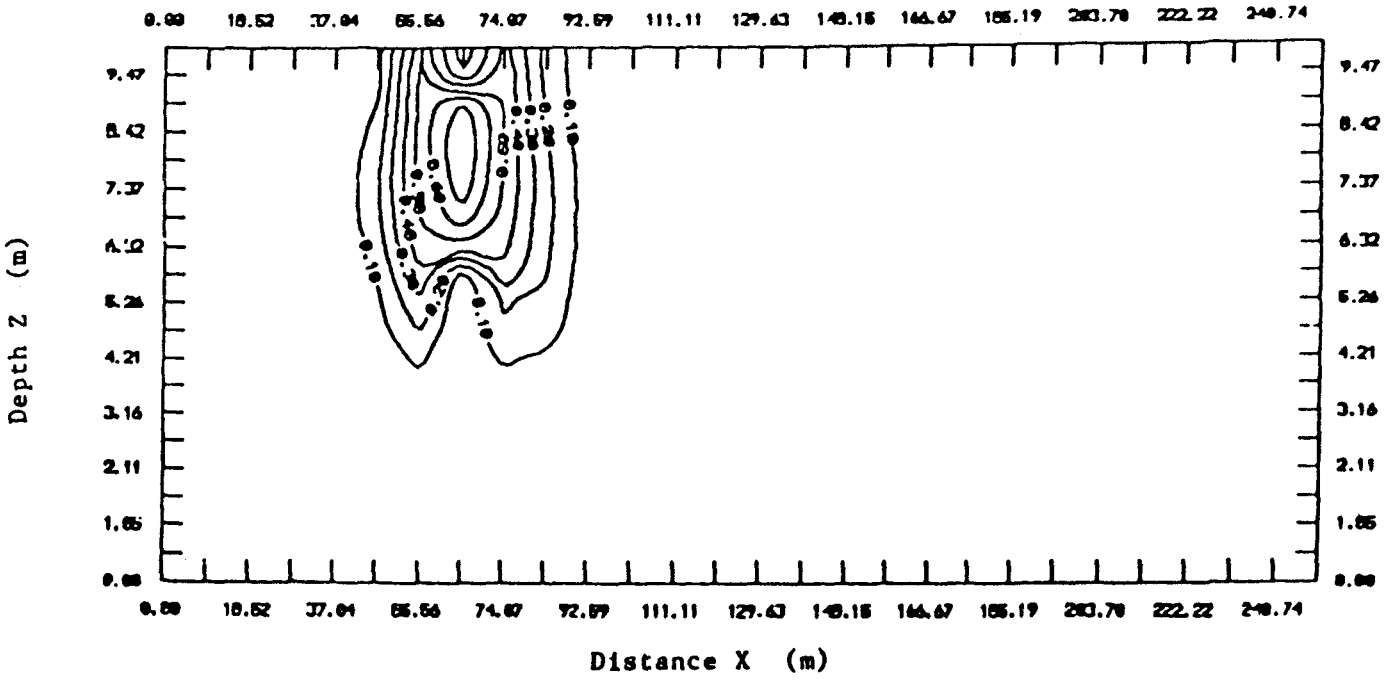

FIGURE 6-7 Saturation of EIC oil at the end of 30 days infiltration

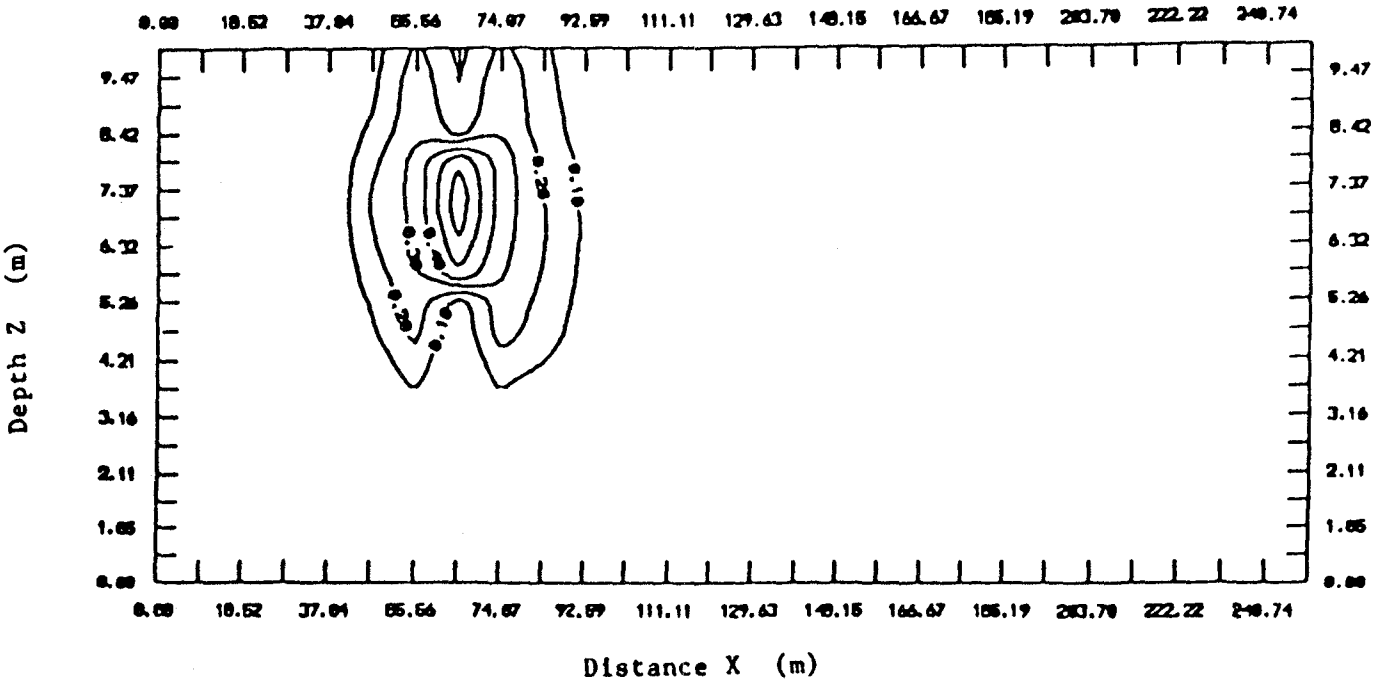

FIGURE 6-8 Saturation of EIC oil at the end of 60 days infiltration

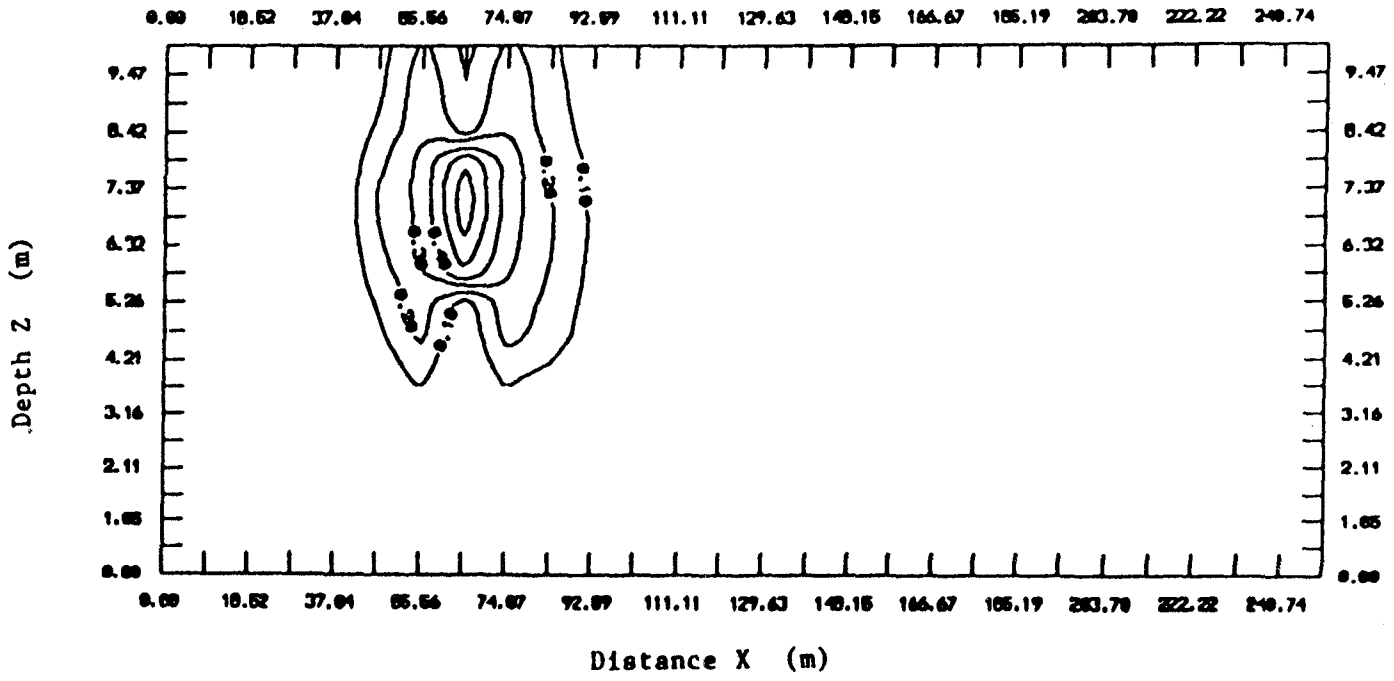

FIGURE 6-9 Saturation of EIC oil at the end of 90 days infiltration

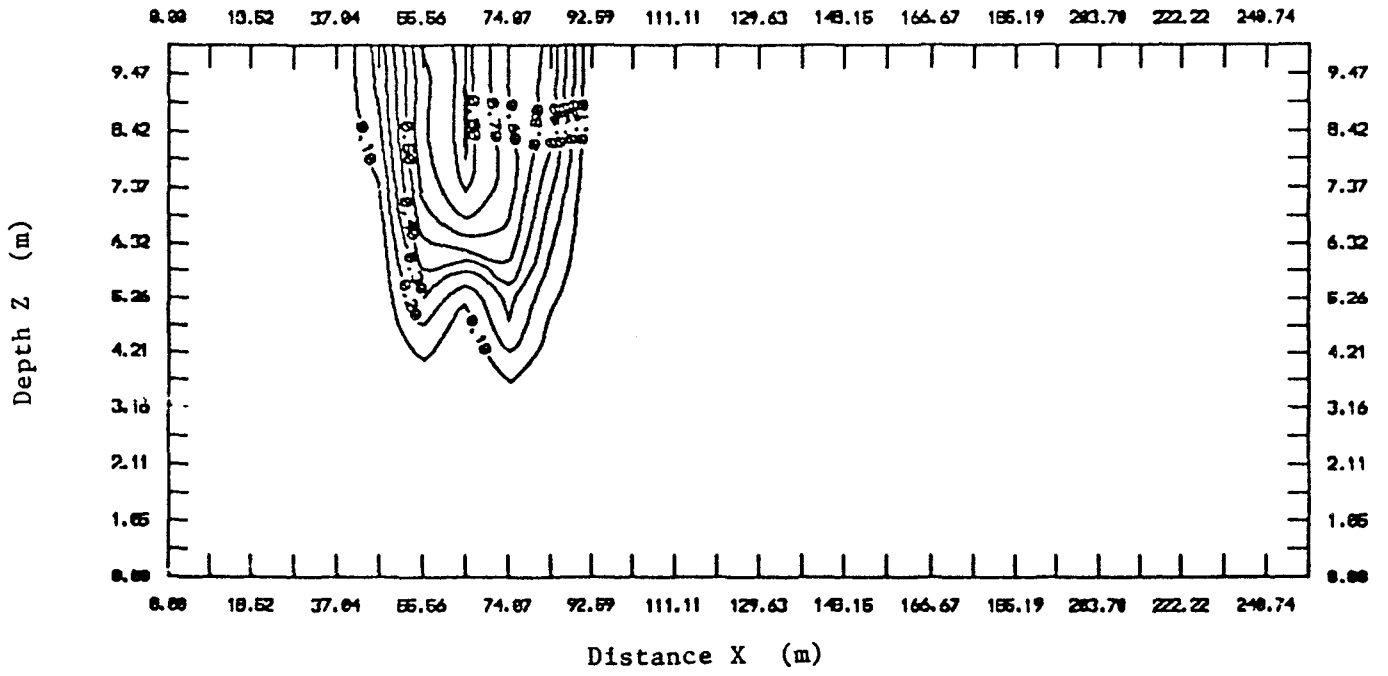

FIGURE 6-10 Saturation of EIC oil at the end of 120 Days Infiltration

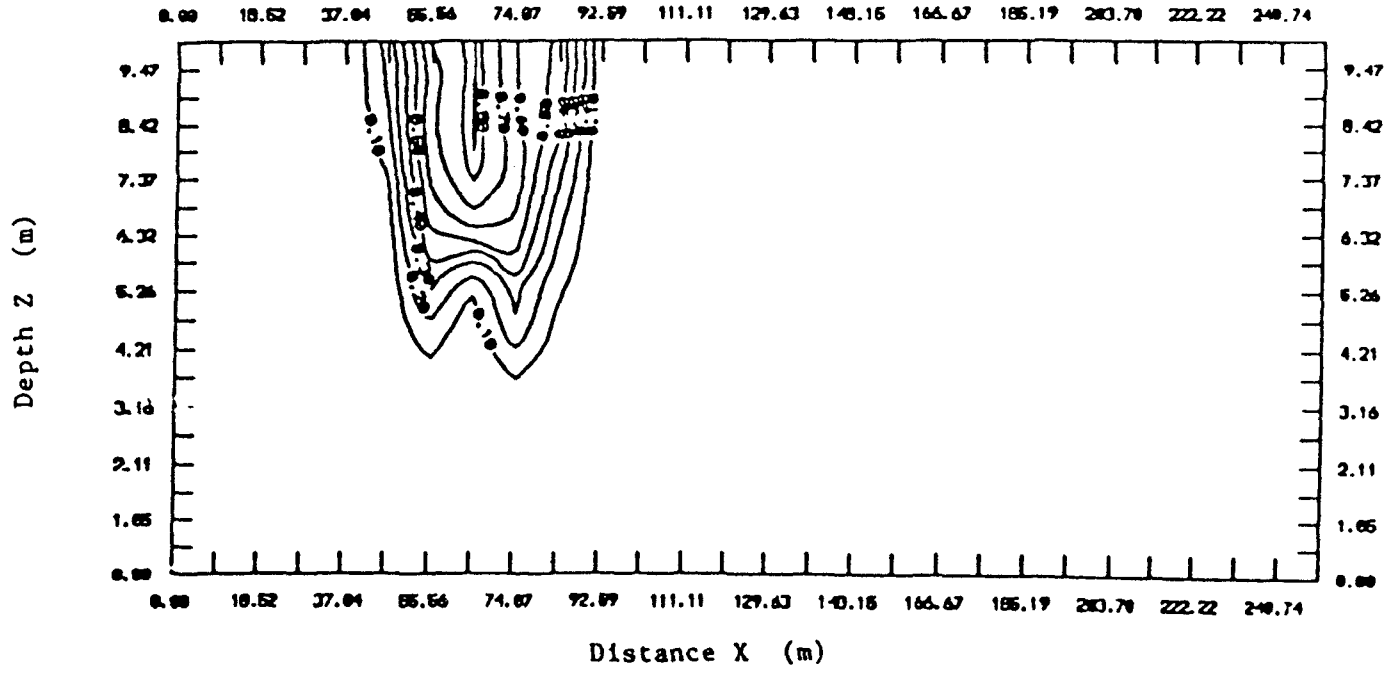

FIGURE 6-11 Predicted water phase concentration plume of benzene at the end of 10 days infiltration

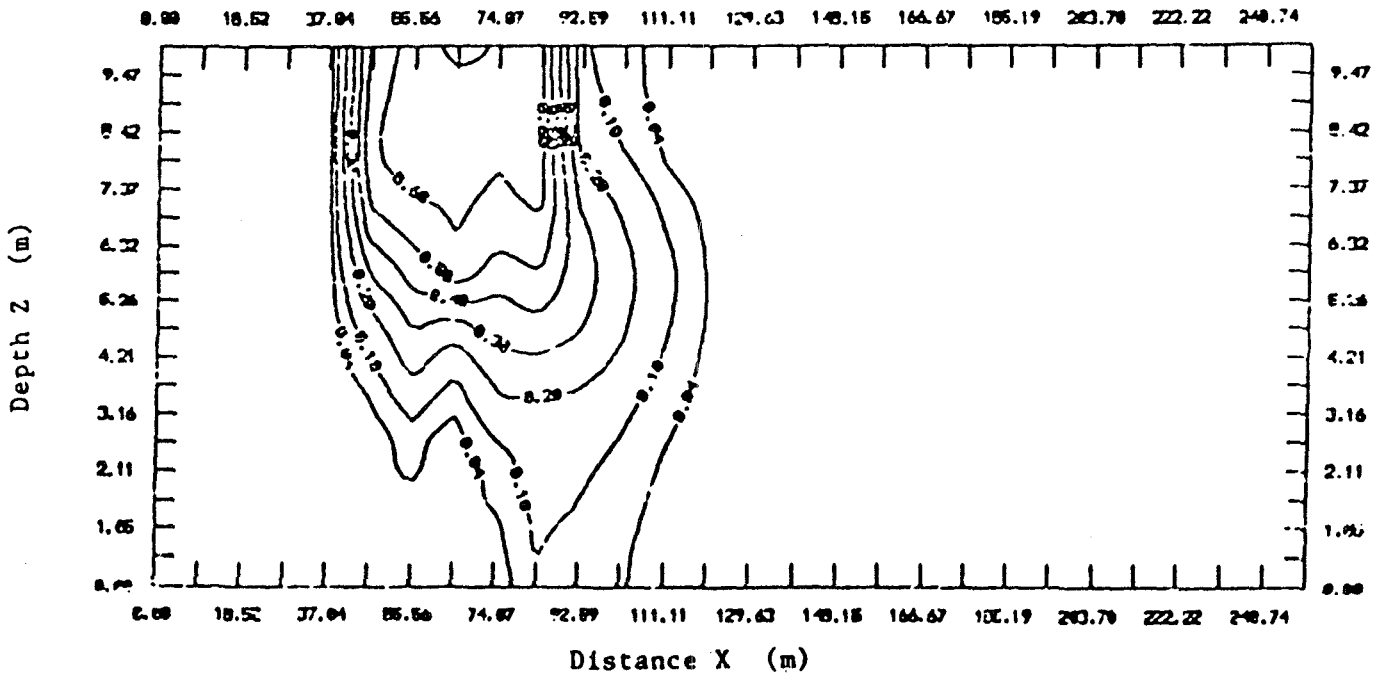

FIGURE 6-12 Predicted water phase concentration plume of benzene at the end of 30 days redistribution

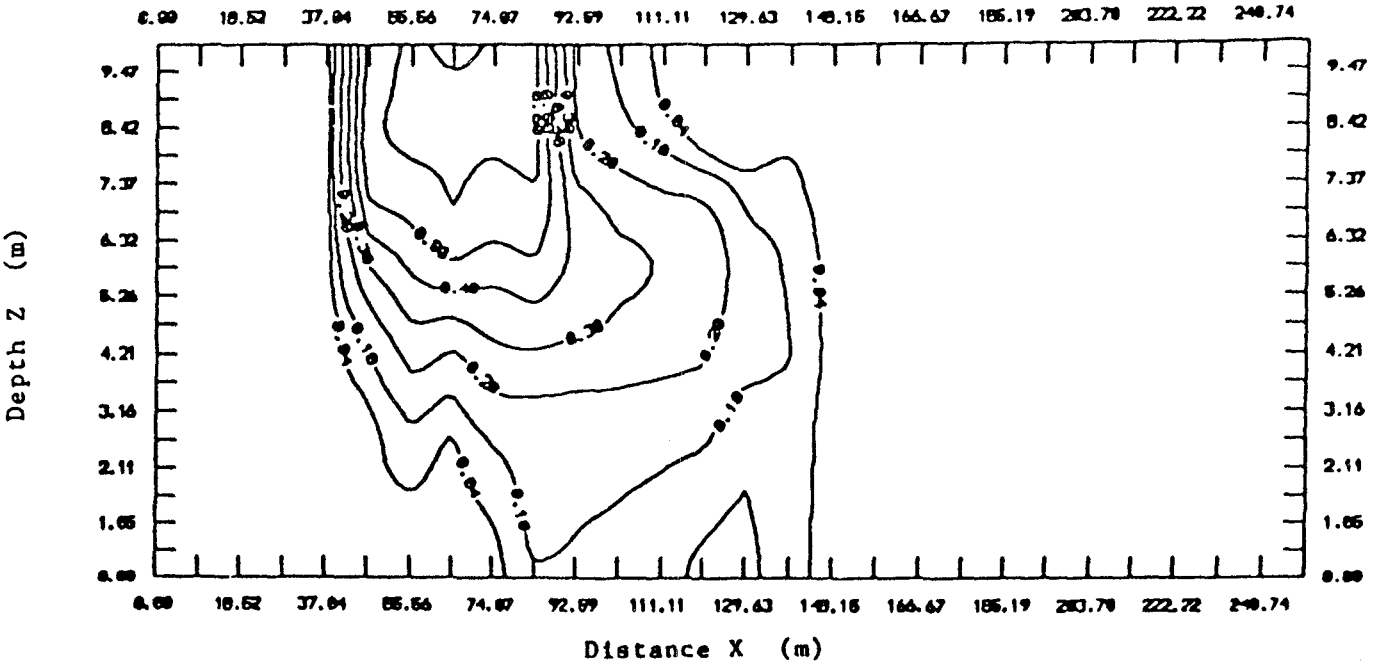

FIGURE 6-13 Predicted water phase concentration plume of benzene at the end of 60 days redistribution

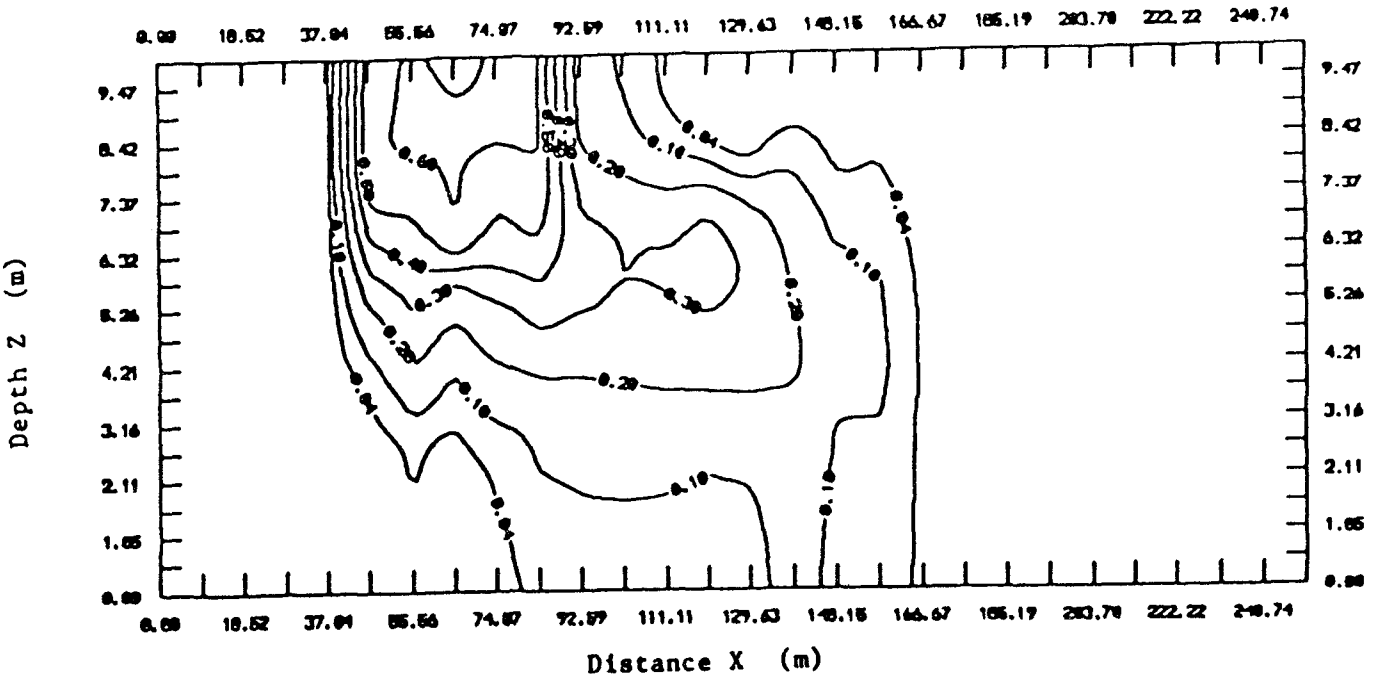

FIGURE 6-14 Predicted water phase concentration plume of benzene at the end of 90 days redistribution

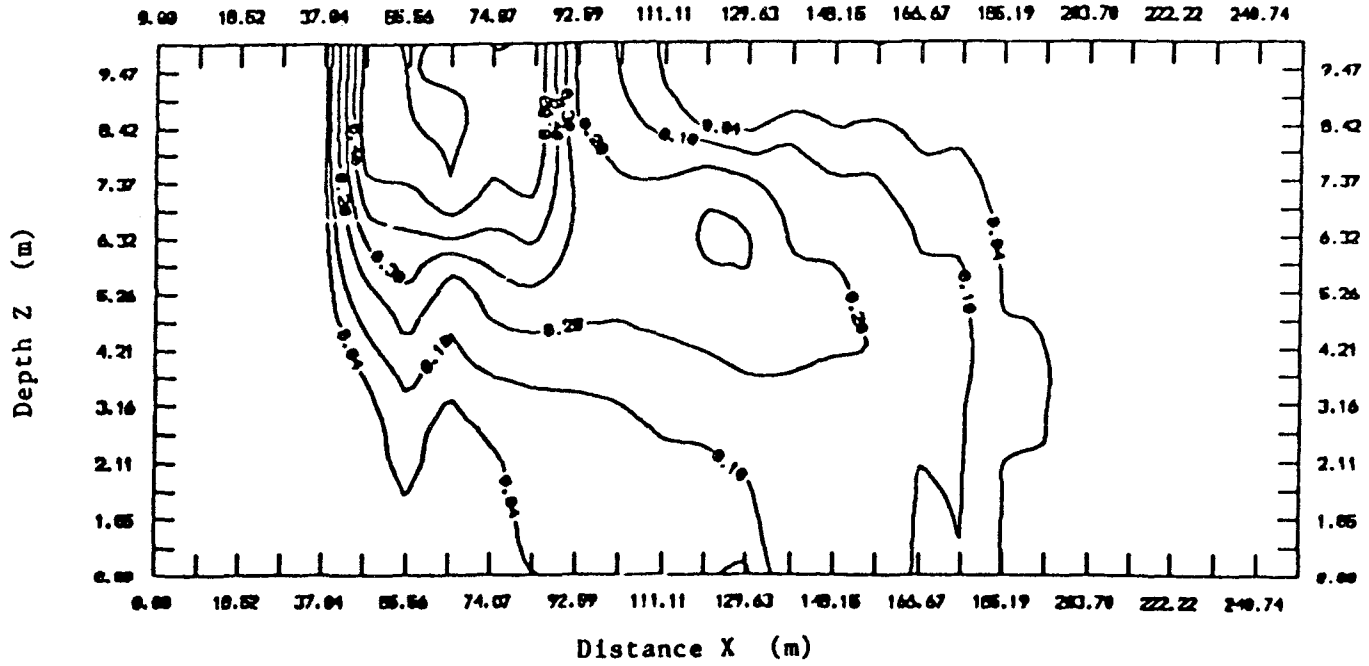

FIGURE 6-15 Predicted water phase concentration plume of benzene at the end of 120 days redistribution

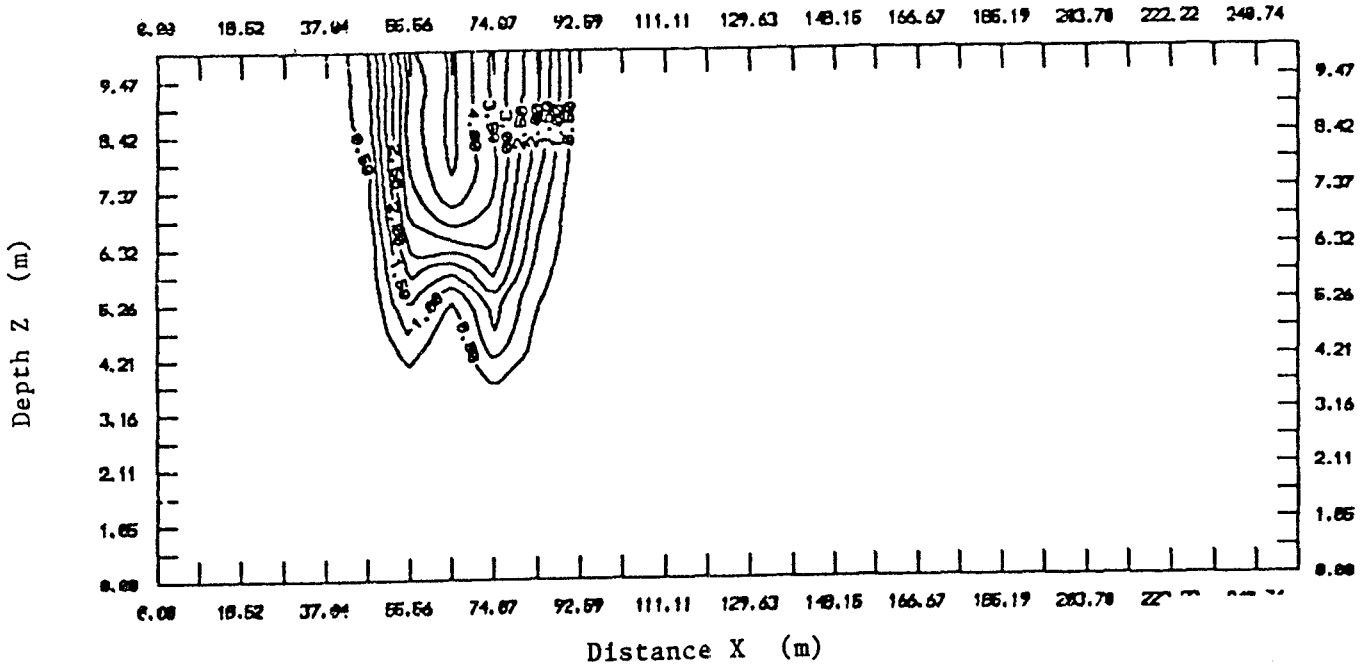

FIGURE 6-16 Predicted water phase concentration plume of toluene at the end of 10 days infiltration

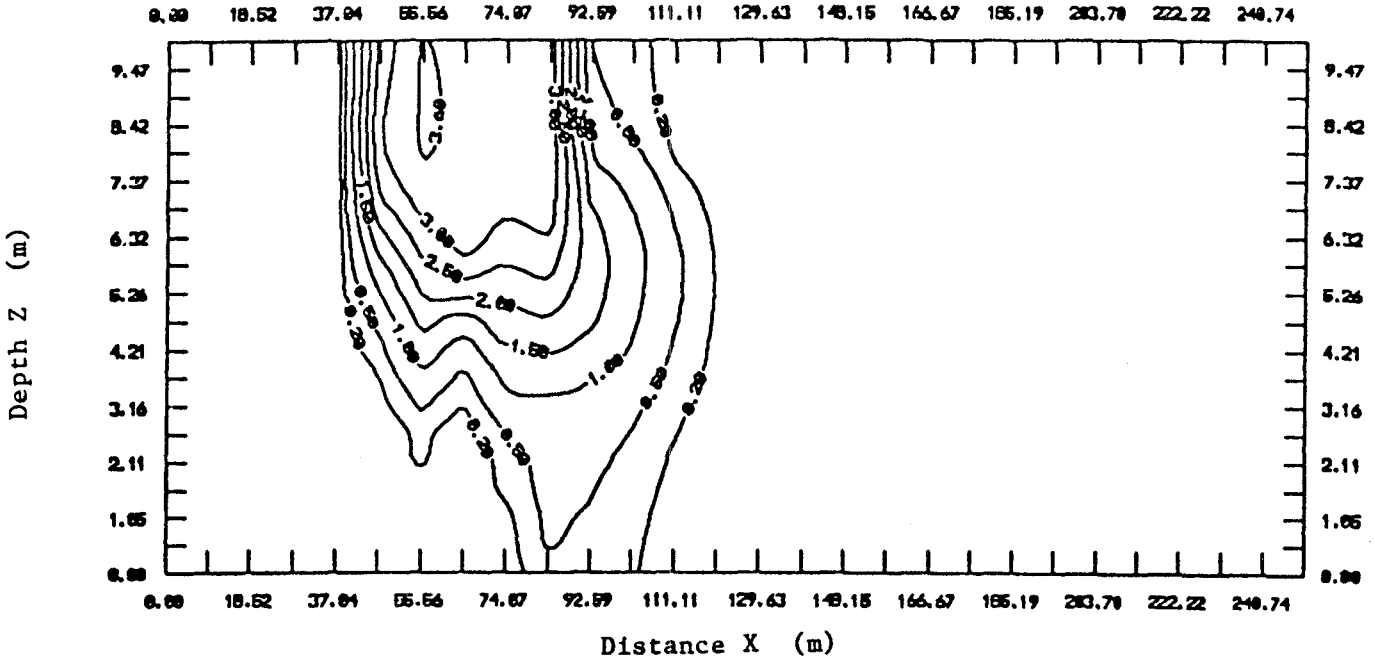

FIGURE 6-17 Predicted water phase concentration plume of toluene at the end of 30 days redistribution

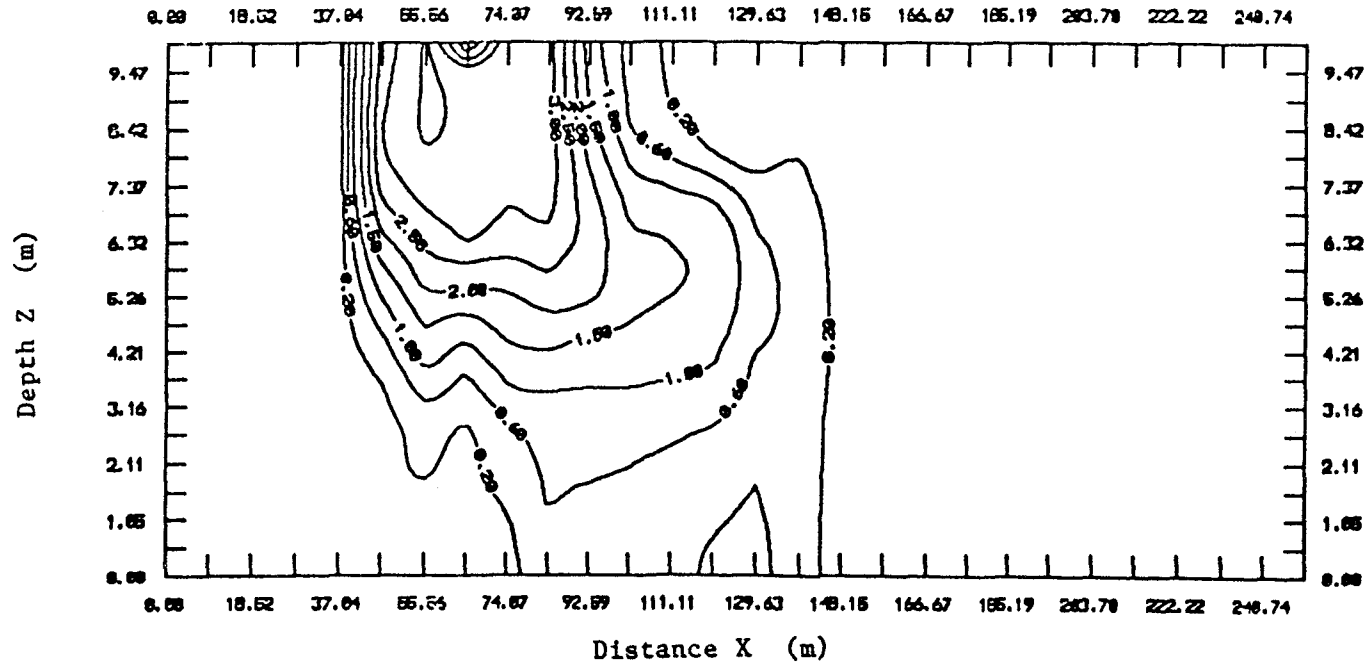

FIGURE 6-18 Predicted water phase concentration plume of toluene at the end of 60 days redistribution

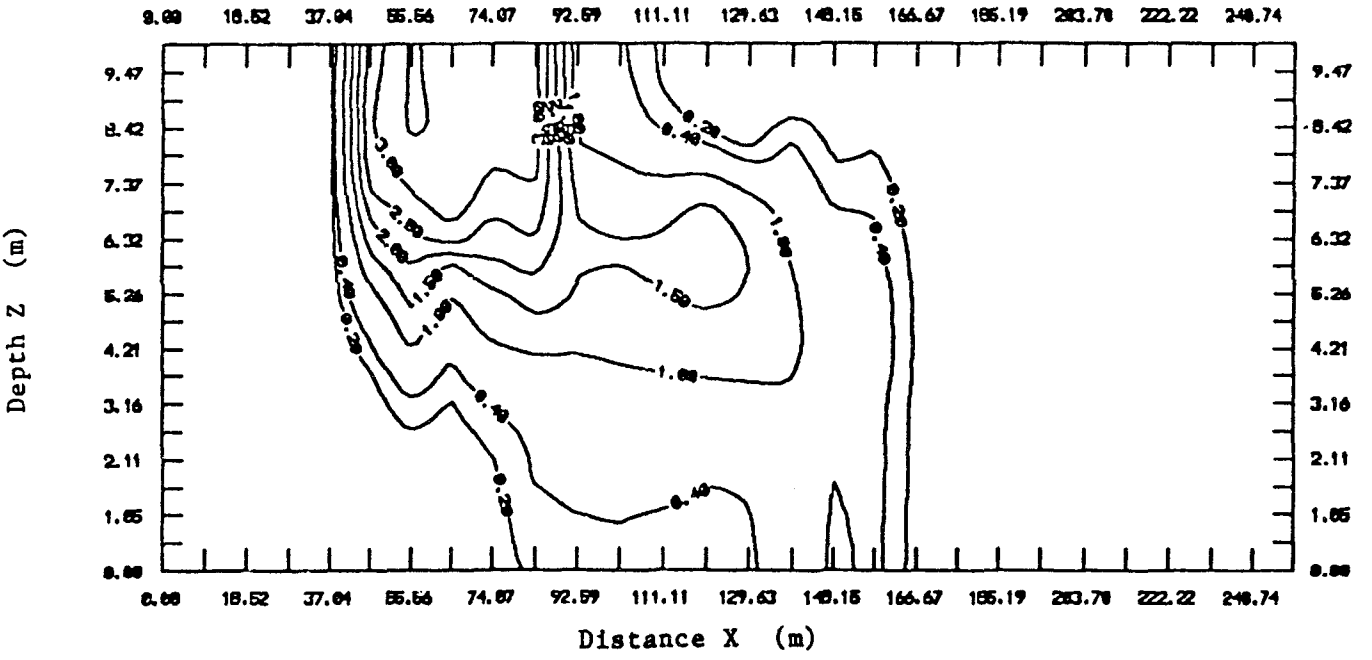

FIGURE 6-19 Predicted water phase concentration plume of toluene at the end of 90 days redistribution

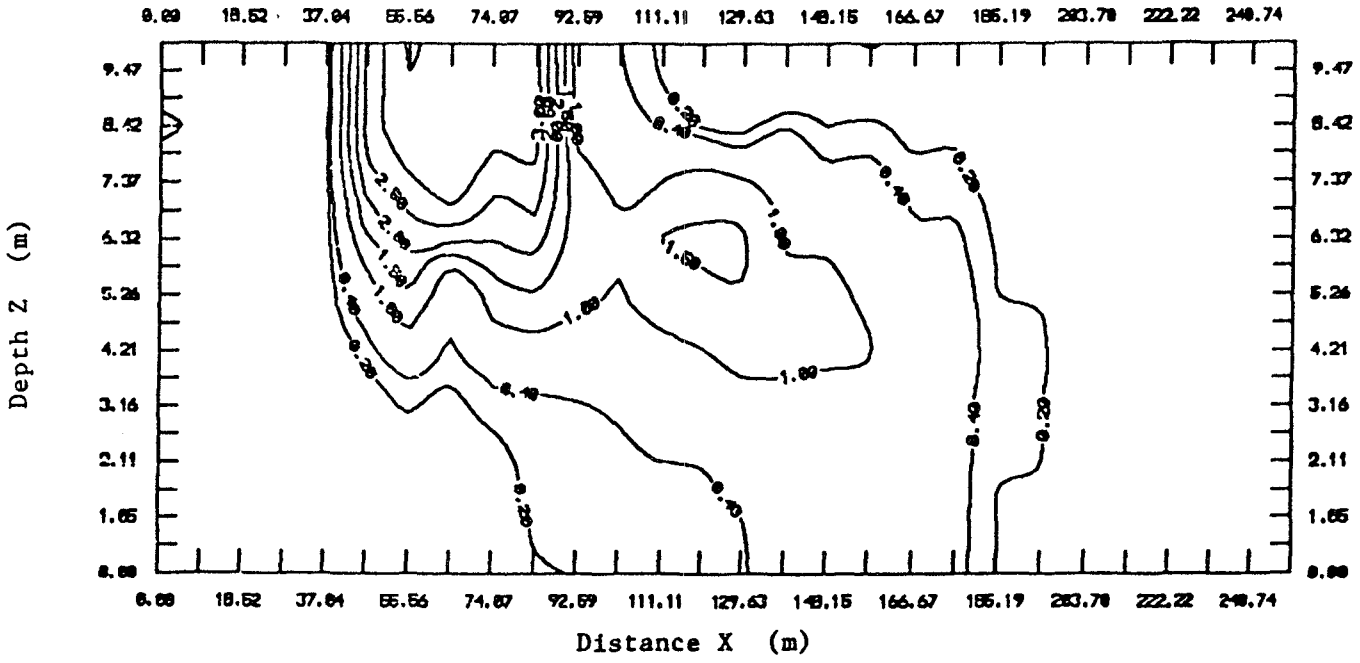

FIGURE 6-20 Predicted water phase concentration plume of toluene at the end of 120 days redistribution

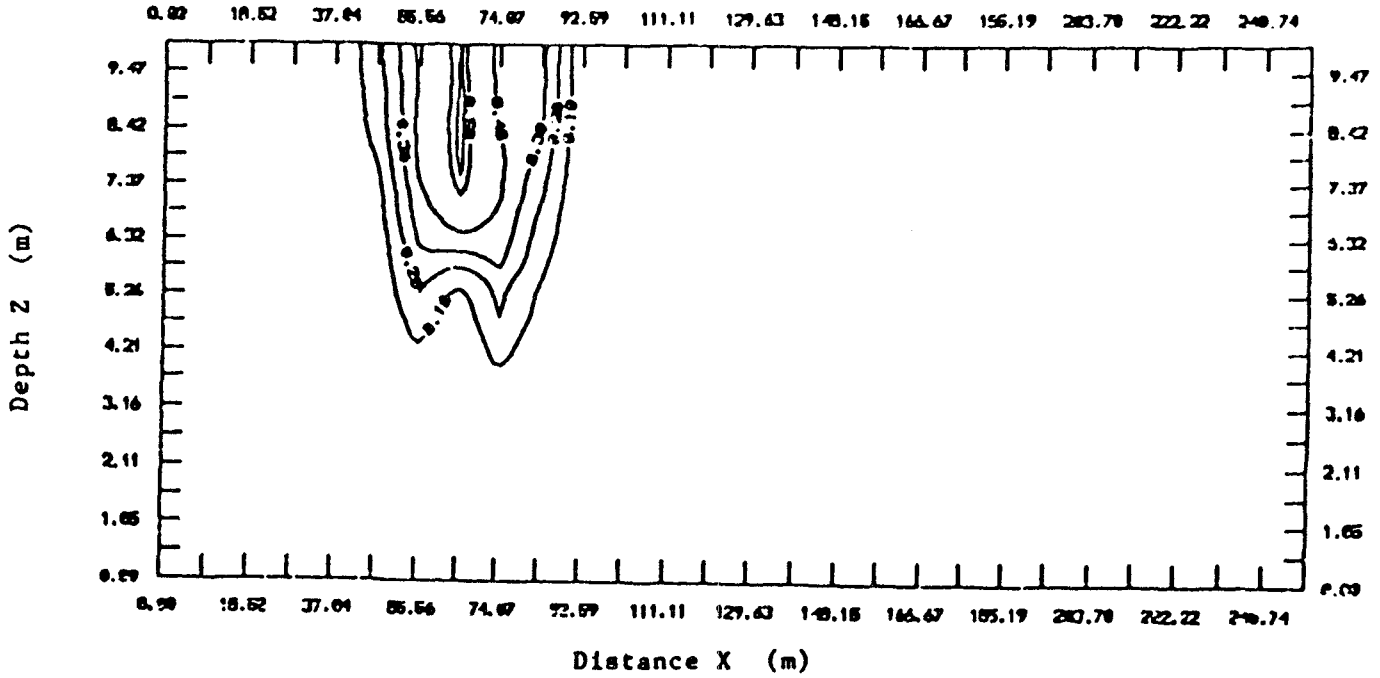

FIGURE 6-21 Predicted water phase concentration plume of ethylbenzene at the end of 10 days infiltration

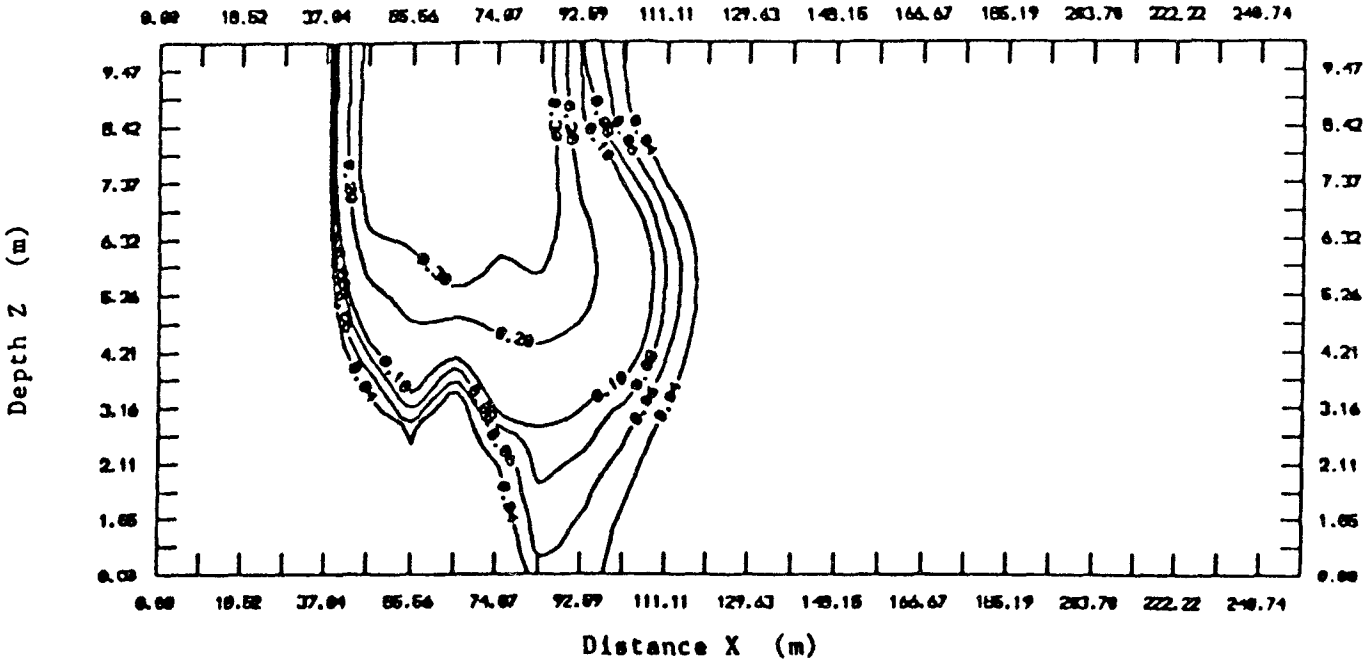

FIGURE 6-22 Predicted water phase concentration plume of ethylbenzene at the end of 30 days redistribution

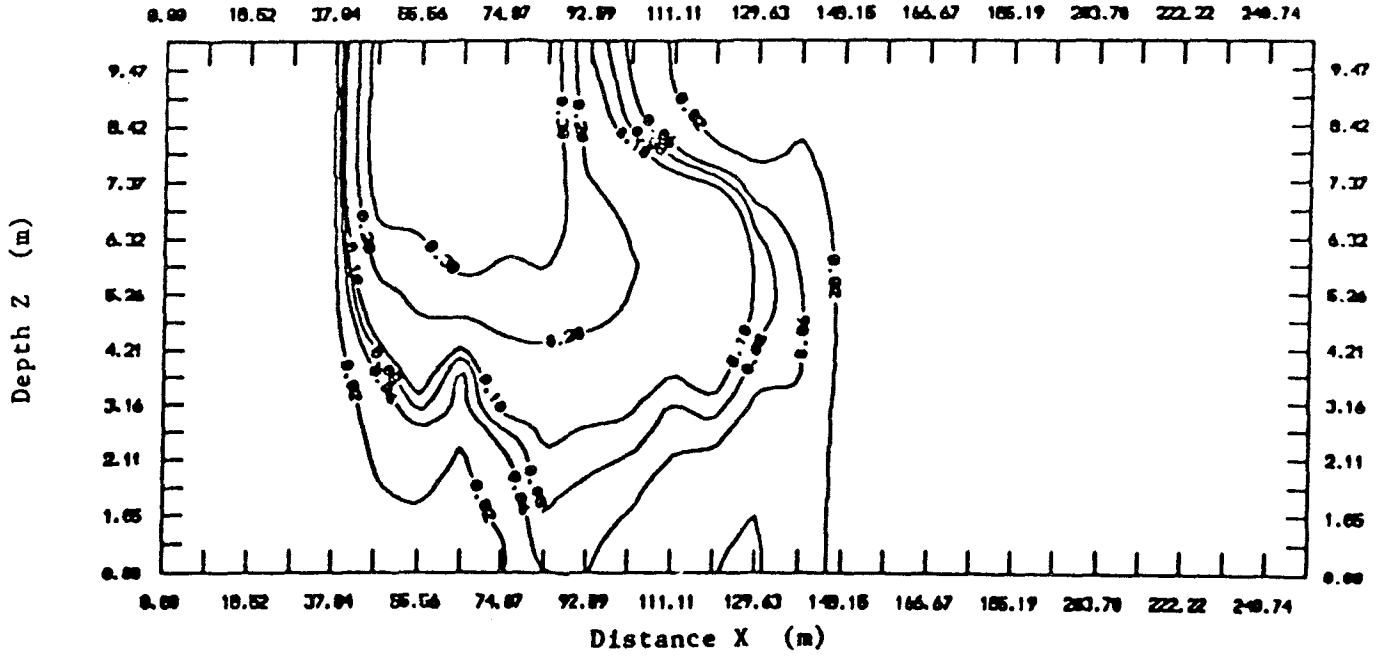

FIGURE 6-23 Predicted water phase concentration plume of ethylbenzene at the end of 60 days redistribution

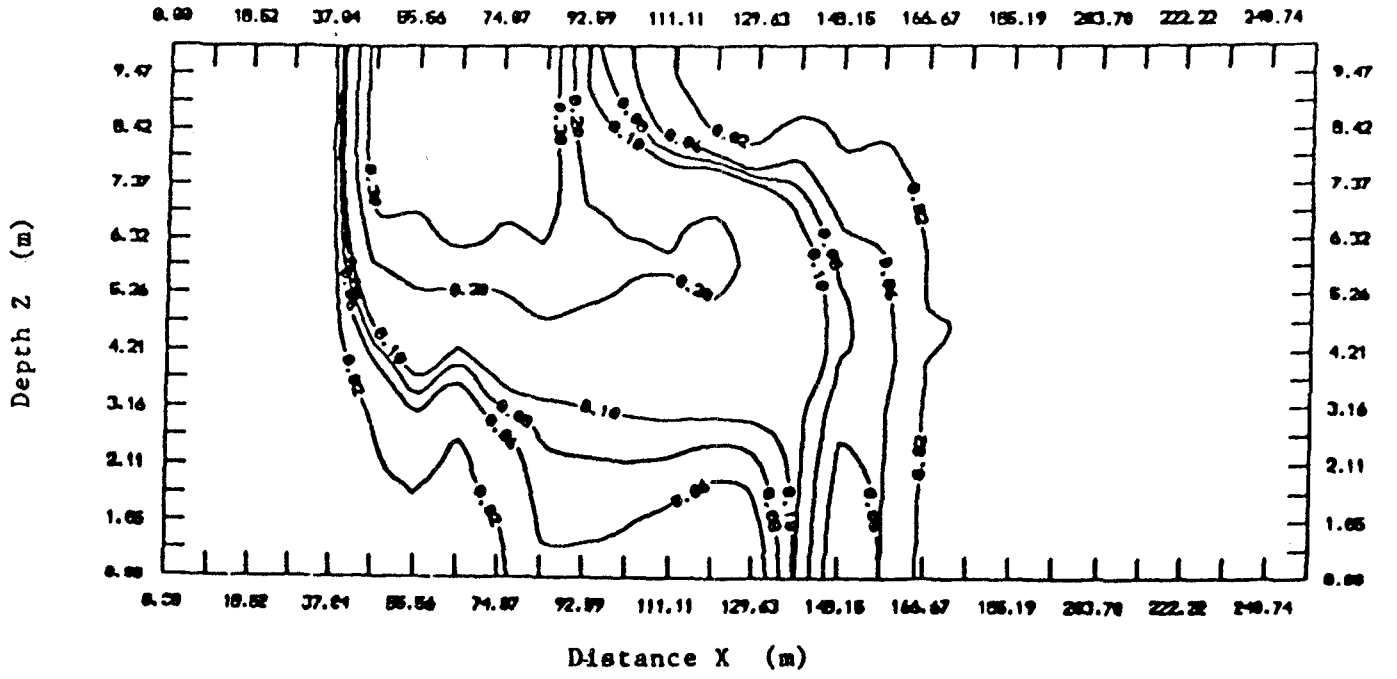

FIGURE 6-24 Predicted water phase concentration plume of ethylbenzene at the end of 90 days redistribution

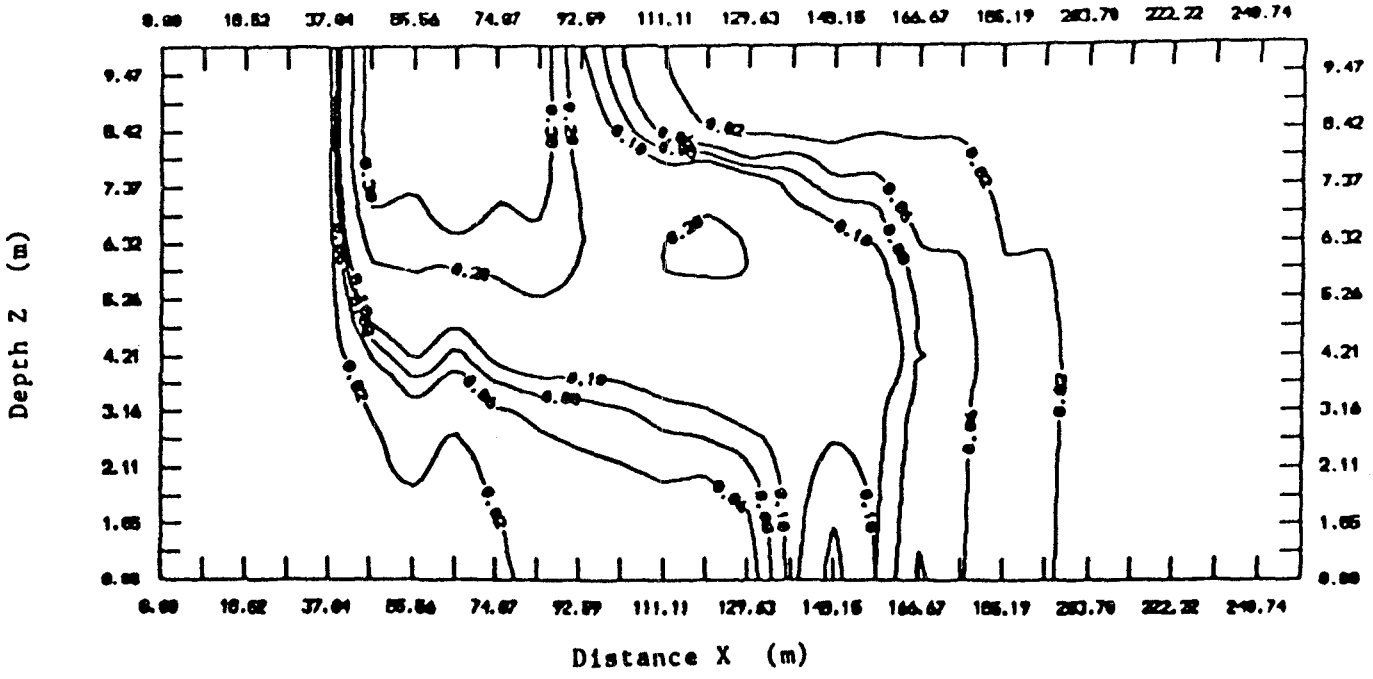

FIGURE 6-25 Predicted water phase concentration plume of ethylbenzene at the end of 120 days redistribution

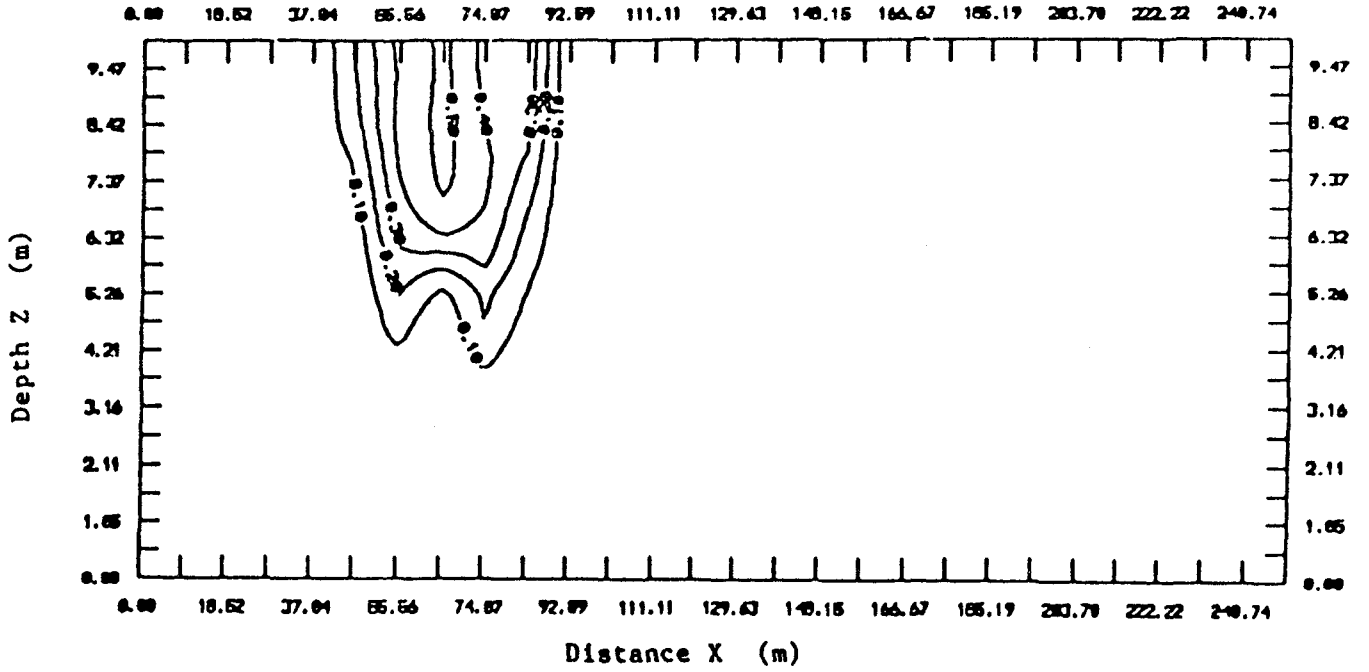

FIGURE 6-26 Predicted water phase concentration plume of oxylene at the end of 10 days infiltration

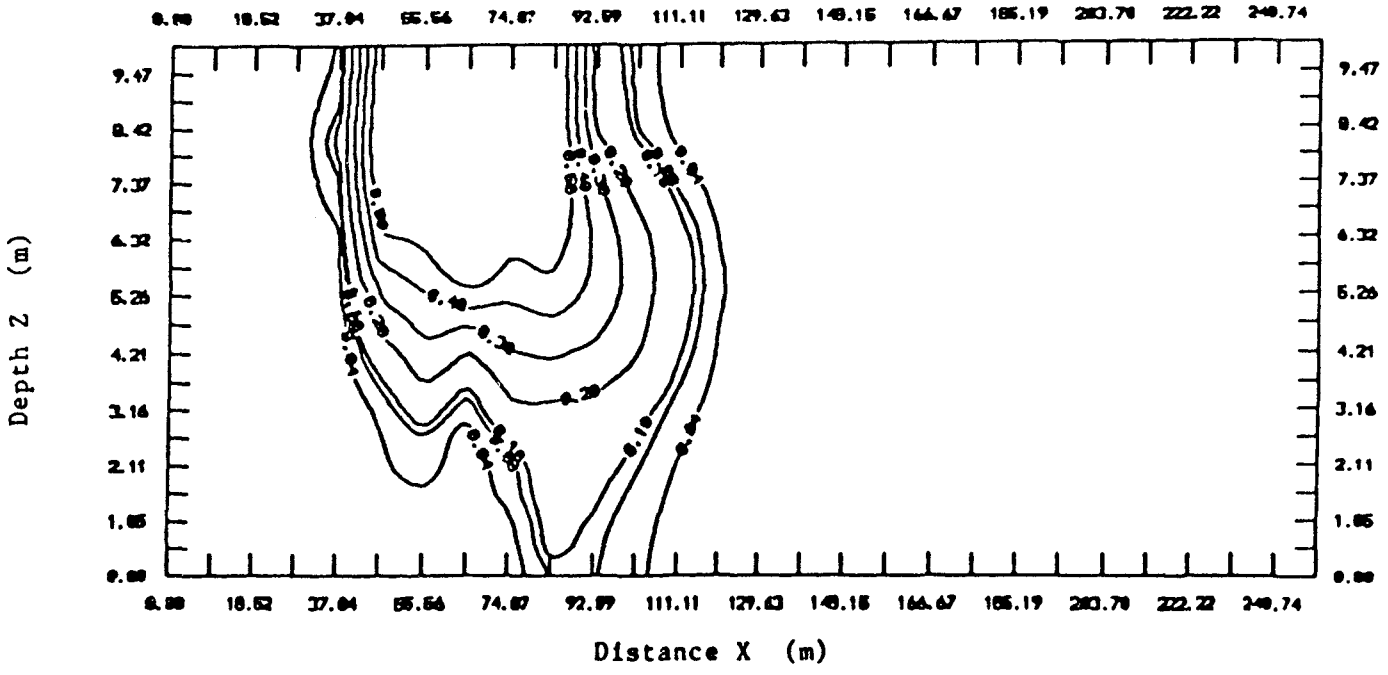

FIGURE 6-27 Predicted water phase concentration plume of oxylene at the end of 30 days redistribution

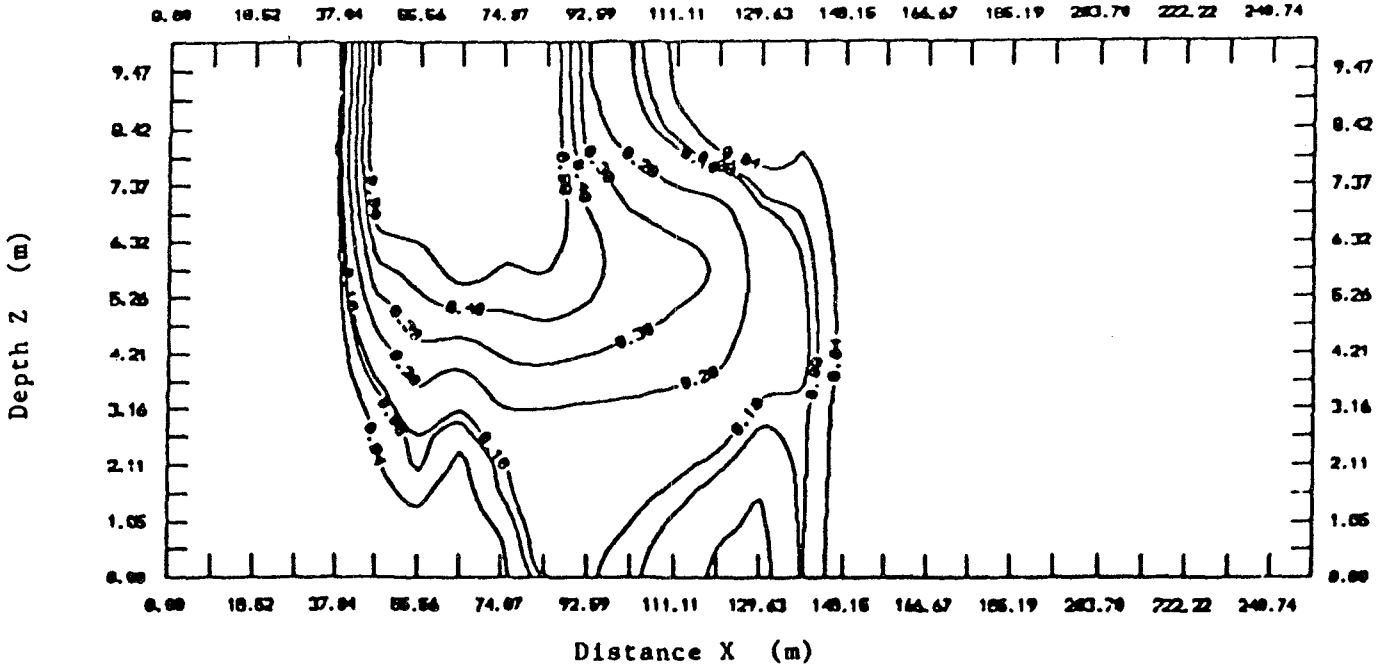

FIGURE 6-28 Predicted water phase concentration plume of oxylene at the end of 60 days redistribution

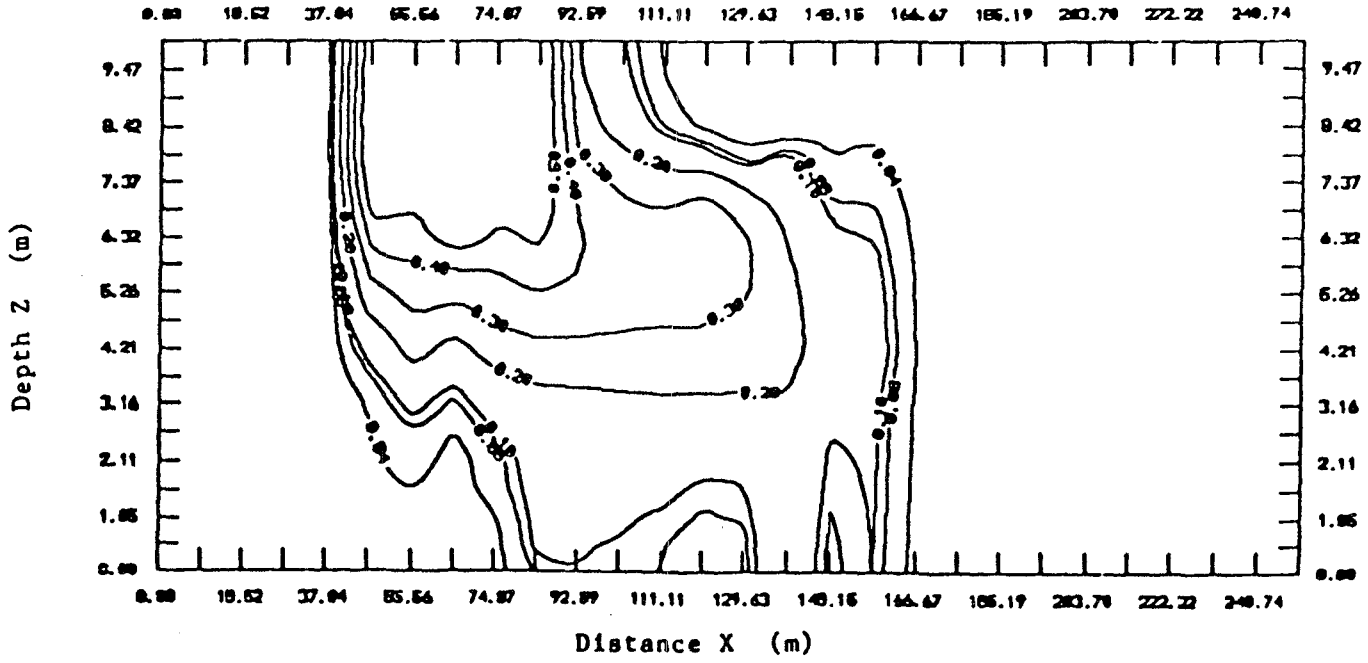

FIGURE 6-29 Predicted water phase concentration plume of oxylene at the end of 90 days redistribution

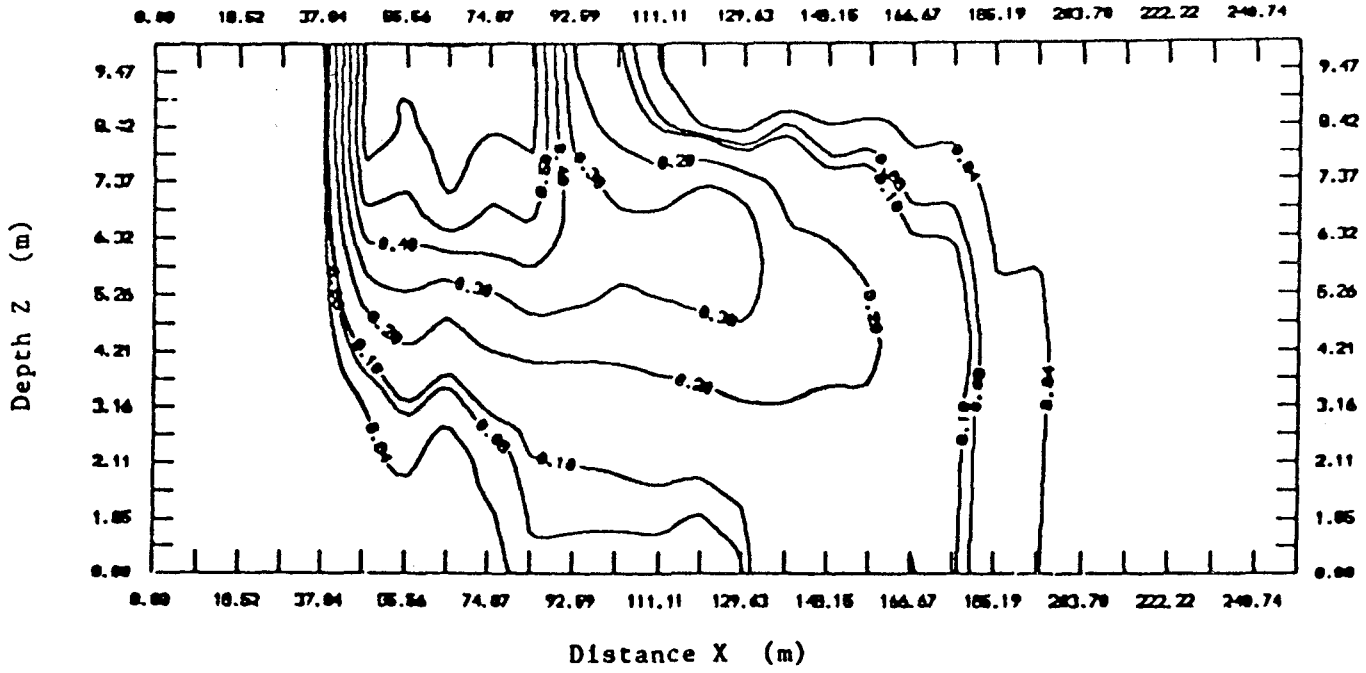

FIGURE 6-30 Predicted water phase concentration plume of oxylene at the end of 120 days redistribution

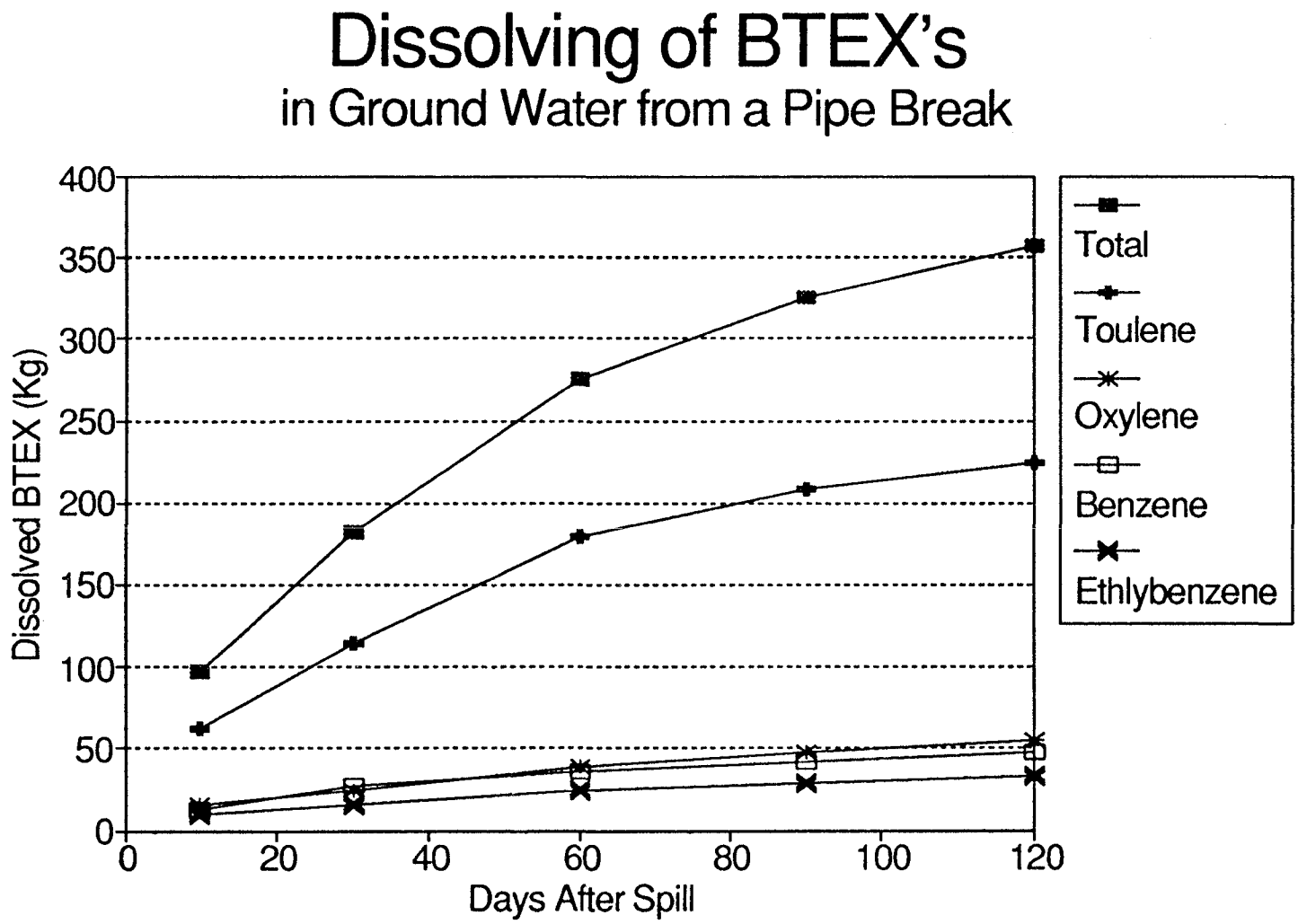

FIGURE 6-31 Mass of BTEX's dissolved in water during the periods of redistribution

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

There are two offsetting factors concerning hydrocarbon spills from ruptured pipe lines. The first is that the infiltration, distribution, and dissolution are slow; moreover, the rate of distribution slows over time. The dissolution, however, continues. In fact for heavier soils, the infiltration would be almost non-existent. Also, less viscous crude oils would not infiltrate, even in soil similar to that used in this study.

The slowness or non-existence of infiltration allows ample time for remediation, even when an unconfined water table is fairly close to the surface. For situations where the water table is significantly deeper, even more time for remediation would be available. This means that emergency measures do not have to be "on the alert" in case of an earthquake, but they should be available to respond within a reasonable time, say a week or so.

The second factor is the magnitude of the spill and the danger from the BTEX's. These features suggest the need for a complete remediation effort; one in which enough of the LNAPL is removed so no health hazard exists. The risk factor would depend on the importance and use of the ground water. It the potential contamination occurs over a sole source aquifer, such as the Memphis Sands, then the clean up standards are more crucial. If, the spill occurs over an aquifer that is only used for irrigation, or even one whose water quality it to low

to be useful, then the success of the cleanup is less important.

Two questions remain; how generally applicable are the results of this project? And, what might be the regional effects? Addressing the regional effects first, a number of pipelines in the area of an earthquake might rupture. This would mean that the remediation resources may be heavily taxed to clean up all the sites within a reasonable period of time.

The results of this project can give a general sense of what any crude oil pipeline might cause if ruptured. Obviously, different soil types will cause the time of the infiltration to vary. Also, the time it takes the LNAPL to reach the water table is a function of the depth to water table. A crude approximation may be attempted by extrapolating these results to other area, taking into account the two main factors, soil hydraulic conductivity, and depth to water table.

7.1 RECOMMENDATIONS

One or more similar studies should be undertaken, especially when the next rupture occurs. An event, similar to the Bemidji spill would offer an excellent opportunity to test the two models used in this study, MOFAT and ARMOS, and see if the estimated parameters closely match the measured spread of the plume. Computer analysis and laboratory tests need to be verified by real world situations.

Oil companies may want to preempt government regulation in planning for such events. In one state, Arkansas, a law exists regulating these pipelines and

the responsibility of the pipe companies. It appears that a number of pipeline companies are unfamiliar with Part 195 Transportation of Hazardous Liquids by Pipeline, of Title 49 Code of Federal Regulations which requires in section 195.260(e) that a valve be installed on each side of a water crossing more than 100 feel wide (high water mark to high water mark). Furthermore, ANSI/ASME B31.4 "Liquid Petroleum Transportation Piping Systems," section 434.15.2 requires mainline block valves at the upstream side of major river crossings and a block or check valve on the downstream side. In addition, the maximum spacing of mainline block valves for liquid petroleum pipe was 10 miles in industrial, commercial, and residential areas. However, the 1981 addenda to B31.4-1979 deleted the 10 mile maximum spacing requirement but left unchanged the river crossing requirements.

It is not clear whether these regulations apply retroactively to existing pipelines, but it does seem clear that no consideration was given to possible ground water contamination from a pipe rupture. What should be added to these regulations is a provision to limit the volume of petroleum spilled over important aquifers. There are several obvious measures of aquifer sensitivity to contamination, one being the importance of the aquifer as a source of water, and the other the ease of remediating the probable spill.

Finally, regional emergency organizations should be aware of the spill potential from earthquakes. A limited survey found that these organizations do not have in place measures for a single, non-earthquake caused spill, let alone one

caused by an earthquake. Emergency plans should be developed in all earthquake zones to handle potential earth quake caused ruptures. First, the number and magnitude of ruptures should be cataloged and second, these potential rupture sites should be prioritized by environmental sensitivity. If this report merely increases awareness to the potential hazard of crude oil pipeline ruptures, it will have been worthwhile.

SECTION 8

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APPENDIX A

SAMPLE CALCULATION OF INPUT DATA

Calculate the specify gravity of the crude oil (EIC)

Gravity API of EIC at 15.6 degree Centigrade (60 degree Fahrenheit) = 33.6
(Refer to Table 4.1)

The specify gravity can be computed from the API gravity as follows:

$$\text{Deg. API} = 141.5/\rho - 131.5$$

where,

API = American Petroleum Institute

ρ = Specify gravity of fraction at (C/C) or (F/F).

$$33.6 = 141.5/\rho - 131.5$$

Therefore,

$$\rho = 141.5/(33.6 + 131.5)$$

$$= 0.857 \quad \text{(at 15.6 degree Centigrade)}$$

Compute the ratio of the density of the crude oil to the density of the water

ρ_{ro} = density of crude/density of water

$= 0.857/1 \quad (gm/cm^3)/(gm/cm^3)$

$= 0.857$

Compute the ratio of the absolute viscosity to the absolute viscosity of the water

The absolute viscosity tabulated in the Table 4.1, is 58.7 SSU at the temperature of 15.6 degree Centigrade. The value is in the Standard Saybolt Unit (SSU). The corresponding value of this absolute viscosity is 8.06 centipoise obtained from the Shell Pipe Line Corporation Personnel. In addition, the kinematic viscosity of the EIC is 9.4 centistoke.

Absolute viscosity of water = 1.122 centipoise

η = (abso. visco. of oil)/(abso. visco. of water)

= 8.06/1.122

= 7.18

Estimate fluid pairs scaling factors

For the unconfined petroleum hydrocarbons, βao and βow may be estimated using the correlation between the oil surface tension and specify gravity given by Baker and Swerdloff (1956), and by Lenhard and Parker (1988).

$\beta ao = 1/(1-(0.5/\rho ro))$

$= 1/(1-(0.5/0.857))$

$= 2.40$

and,

$\beta ow = 2\rho ro$

$= 2 \times 0.857$

$= 1.72$

Compute the value of H^{min}

$H^{min} = h_d \times [1/(\beta ow \times (1 - \rho ro)) - 1/(\beta ao \times \rho ro)]$

$= 0.0541 \times [1/(1.71 \times (1 - 0.857)) - 1/(2.40 \times 0.857)]$

$= 0.1949$ meter

Estimate the volume of crude in the vertical porous media simulation (MOFAT Simulation)

The estimation of the volume in the vertical porous media is assumed that the water table is level and the slope of the oil (NAPL) is linear.

The V_0 values illustrated in the sketched triangle as shown below were obtained from the ARMOS Simulation of the 10 days infiltration. The location of the V_0 was selected at the location of the probable break point that is about 65 meters from the left of the domain and the triangle is constructed by extending the line from this point in the vertical section by referring to Figure A-1.

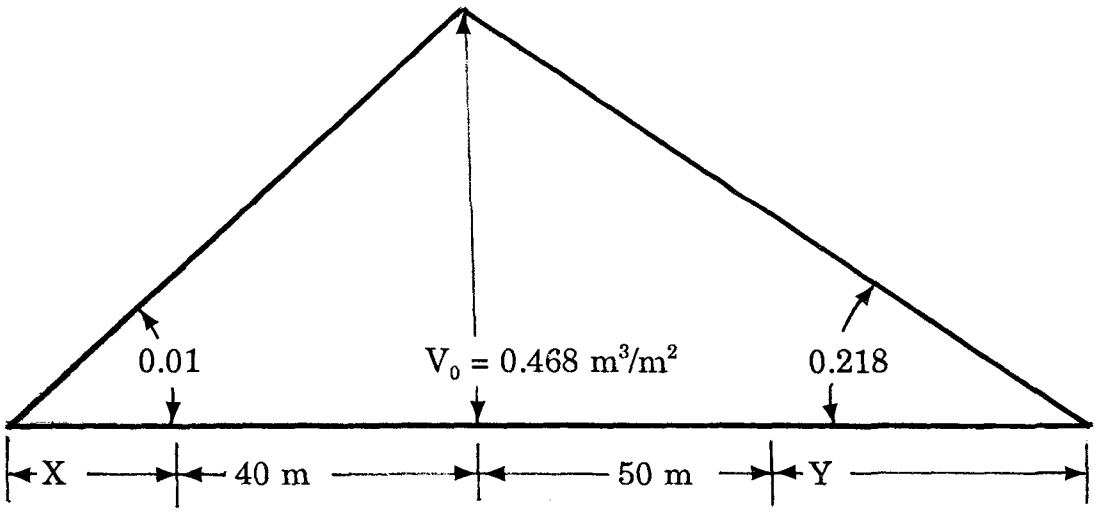

Figure A-1. Cross Section of NAPL lens

To estimate the distance of X:

$X/0.010 = (40 + X)/0.468$

$0.468X = 0.4 + 0.010X$

$0.485X = 0.4$

$X = 0.4/0.458$

$= 0.87$ m

To estimate the distance of Y:

$Y/0.218 = (50 + Y)/0.468$

$0.468Y = 10.9 + 0.218Y$

$0.25Y = 10.9$

$Y = 10.9/0.25$

$= 43.6$ m

The total distance is approximately 135 meters.

Therefore,

Area of the triangle = 1/2 x 135 x 0.468

$= 32$ m^3/m

For the modeling standpoint, the predicted probable volume of oil in the vertical porous media is 32 m^3/m and the probable volume of oil infiltrating in the horizontal porous media can be approximately estimated based on the above results; the estimation is as following:

Assuming the volume of the oil in the horizontal porous media is approximately the volume of a cone.

Volume $= 1/3 \times 3.1415927 \times r^2 \times h$

$= 1/3 \times 3.1415927 \times (135/2)^2 \times V_o$

$= 1/3 \times 3.1415927 \times (68)^2 \times 0.468$

$= 2266$ m^3

For reporting purposes, the V = 2266 m^3 is reported approximately as 2260 m^3 throughout this report. This amount of oil is approximately 40 percent of the total probable spill volume which is initially estimated by calculating the volume in pipeline between the two surrounding high elevations, and then by subtracting the oil that would collect in the valleys between the ridges, refer to figure 2.

APPENDIX B INPUT DATA SET FOR ARMOS SIMULATION

```
SIMULATION OF EIC MIGRATION FOR A PERIOD OF 10 DAYS
  0   2   0   2
  0   0 486  18  27   0   1  36   0  41   3
  2   7  27   0
  1    .0000
  3  40.0000
  5  70.0000
  8 100.0000
 12 120.0000
 16 160.0000
 18 200.0000
   .0000  20.0000  35.0000  50.0000  55.0000  60.0000  65.0000
 70.0000  75.0000  80.0000  90.0000 100.0000 110.0000 115.0000
120.0000 125.0000 130.0000 135.0000 140.0000 150.0000 160.0000
175.0000 190.0000 205.0000 220.0000 235.0000 250.0000
  1  82.2960 91.4400
   .0541    .6421   0.5524    .3500  54.3080  54.3080
   .8570   7.1800   2.4000   1.7143
  1  88.7246
  1   0.1944
  1   1
   .0000    .1000  10.0000    .1000  10.0000   1.0500   2.0000
500   4  15   0    .0100    .0010    .0010    .1000
  1   2   0
  2   2   0
  3   2   0
  4   2   0
  5   2   0
  6   2   0
  7   2   0
  8   2   0
  9   2   0
 10   2   0
 11   2   0
 12   2   0
 13   2   0
 14   2   0
 15   2   0
 16   2   0
 17   2   0
 18   2   0
469   3   0
```

```
470   3   0
471   3   0
472   3   0
473   3   0
474   3   0
475   3   0
476   3   0
477   3   0
478   3   0
479   3   0
480   3   0
481   3   0
482   3   0
483   3   0
484   3   0
485   3   0
486   3   0
  0   -.4000    -.4000     .0010     .0003
 42   2   0   1    .0000
 44   2   0   1    .0000
 46   2   0   1    .0000
 48   2   0   1    .0000
 50   2   0   1    .0000
 60   2   0   1    .0000
 62   2   0   1    .0000
 64   2   0   1    .0000
 66   2   0   1    .0000
 68   2   0   1    .0000
 77   2   0   1    .0000
 87   2   0   1    .0000
 98   2   0   1    .0000
100   2   0   1    .0000
102   2   0   1    .0000
114   2   0   1    .0000
122   2   0   1    .0000
131   2   0   1    .0000
134   2   0   1    .0000
136   2   0   1    .0000
138   2   0   1    .0000
141   2   0   1    .0000
168   2   0   1    .0000
170   2   0   1    .0000
172   2   0   1    .0000
174   2   0   1    .0000
```

```
176   2   0   1    .0000
185   2   0   1    .0000
195   2   0   1    .0000
204   2   0   1    .0000
206   2   0   1    .0000
208   2   0   1    .0000
210   2   0   1    .0000
212   2   0   1    .0000
240   2   0   1    .0000
242   2   0   1    .0000
245   2   0   1    .0000
247   2   0   1    .0000
296   2   0   1    .0000
298   2   0   1    .0000
299   2   0   1    .0000
  3   0.0000    0.1000   -0.1944    0.0000
  0   0.1000    2.0000    0.0000   -6.2500
  0   2.0000   40.0000   -6.2500    0.0000
  2   0.0000    1.0000   88.7246   88.6968
  0   1.0000   40.0000   88.6968   88.6968
  4   0.0000    1.0000   88.7246   88.6968
  0   1.0000    1.5000   88.6968   88.0872
  0   1.5000    2.0000   88.0872   87.4776
  0   2.0000   40.0000   87.4776   87.4776
  0
```

```
SIMULATION OF EIC MIGRATION FOR A PERIOD OF 30 DAYS
  0   2   0   2
  0   0 486  18  27   0   1  36   0  41   3
  2   7  27   0
  1    .0000
  3  40.0000
  5  70.0000
  8 100.0000
 12 120.0000
 16 160.0000
 18 200.0000
   .0000  20.0000  35.0000  50.0000  55.0000  60.0000
 65.0000
 70.0000  75.0000  80.0000  90.0000 100.0000 110.0000
115.0000
120.0000 125.0000 130.0000 135.0000 140.0000 150.0000
160.0000
175.0000 190.0000 205.0000 220.0000 235.0000 250.0000
  1  82.2960 91.4400
   .0541   .6421  0.5524   .3500  54.3080  54.3080
   .8570  7.1800  2.4000  1.7143
  1  88.7246
  1   0.1944
  1   1
   .0000   .1000  30.0000   .1000  30.0000  1.0500  10.0000
500   4  15   0   .0100   .0010   .0010   .1000
  1   2   0
  2   2   0
  3   2   0
  4   2   0
  5   2   0
  6   2   0
  7   2   0
  8   2   0
  9   2   0
 10   2   0
 11   2   0
 12   2   0
 13   2   0
 14   2   0
 15   2   0
 16   2   0
 17   2   0
```

```
 18   2   0
469   3   0
470   3   0
471   3   0
472   3   0
473   3   0
474   3   0
475   3   0
476   3   0
477   3   0
478   3   0
479   3   0
480   3   0
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482   3   0
483   3   0
484   3   0
485   3   0
486   3   0
  0   -.4000   -.4000    .0010    .0003
 42   2   0   1    .0000
 44   2   0   1    .0000
 46   2   0   1    .0000
 48   2   0   1    .0000
 50   2   0   1    .0000
 60   2   0   1    .0000
 62   2   0   1    .0000
 64   2   0   1    .0000
 66   2   0   1    .0000
 68   2   0   1    .0000
 77   2   0   1    .0000
 87   2   0   1    .0000
 98   2   0   1    .0000
100   2   0   1    .0000
102   2   0   1    .0000
114   2   0   1    .0000
122   2   0   1    .0000
131   2   0   1    .0000
134   2   0   1    .0000
136   2   0   1    .0000
138   2   0   1    .0000
141   2   0   1    .0000
168   2   0   1    .0000
170   2   0   1    .0000
```

```
172   2   0   1    .0000
174   2   0   1    .0000
176   2   0   1    .0000
185   2   0   1    .0000
195   2   0   1    .0000
204   2   0   1    .0000
206   2   0   1    .0000
208   2   0   1    .0000
210   2   0   1    .0000
212   2   0   1    .0000
240   2   0   1    .0000
242   2   0   1    .0000
245   2   0   1    .0000
247   2   0   1    .0000
296   2   0   1    .0000
298   2   0   1    .0000
299   2   0   1    .0000
  5   0.0000    0.1000   -0.1944    0.0000
  0   0.1000    2.0000    0.0000   -6.2500
  0   2.0000    3.0000   -6.2500  -11.0000
  0   3.0000   10.0000  -11.0000    0.0000
  0  10.0000   60.0000    0.0000    0.0000
  2   0.0000    1.0000   88.7246   88.6968
  0   1.0000   60.0000   88.6968   88.6968
  4   0.0000    1.0000   88.7246   88.6968
  0   1.0000    1.5000   88.6968   88.0872
  0   1.5000    2.0000   88.0872   87.4776
  0   2.0000   60.0000   87.4776   87.4776
  0
```

```
SIMULATION OF EIC MIGRATION FOR A PERIOD OF 60 DAYS
  0   2   0   2
  0   0 486  18  27   0   1  36   0  41   3
  2   7  27   0
  1    .0000
  3  40.0000
  5  70.0000
  8 100.0000
 12 120.0000
 16 160.0000
 18 200.0000
   .0000  20.0000  35.0000  50.0000  55.0000  60.0000  65.0000
 70.0000  75.0000  80.0000  90.0000 100.0000 110.0000 115.0000
120.0000 125.0000 130.0000 135.0000 140.0000 150.0000 160.0000
175.0000 190.0000 205.0000 220.0000 235.0000 250.0000
  1  82.2960  91.4400
   .0541    .6421   0.5524    .3500  54.3080  54.3080
   .8570   7.1800   2.4000   1.7143
  1  88.7246
  1   0.1944
  1   1
   .0000    .1000  60.0000    .1000  60.0000   1.0500  10.0000
500   4  15   0    .0100    .0010    .0010    .1000
  1   2   0
  2   2   0
  3   2   0
  4   2   0
  5   2   0
  6   2   0
  7   2   0
  8   2   0
  9   2   0
 10   2   0
 11   2   0
 12   2   0
 13   2   0
 14   2   0
 15   2   0
 16   2   0
 17   2   0
 18   2   0
469   3   0
470   3   0
471   3   0
```

```
472   3   0
473   3   0
474   3   0
475   3   0
476   3   0
477   3   0
478   3   0
479   3   0
480   3   0
481   3   0
482   3   0
483   3   0
484   3   0
485   3   0
486   3   0
  0   -.4000   -.4000    .0010    .0003
 42   2   0   1    .0000
 44   2   0   1    .0000
 46   2   0   1    .0000
 48   2   0   1    .0000
 50   2   0   1    .0000
 60   2   0   1    .0000
 62   2   0   1    .0000
 64   2   0   1    .0000
 66   2   0   1    .0000
 68   2   0   1    .0000
 77   2   0   1    .0000
 87   2   0   1    .0000
 98   2   0   1    .0000
100   2   0   1    .0000
102   2   0   1    .0000
114   2   0   1    .0000
122   2   0   1    .0000
131   2   0   1    .0000
134   2   0   1    .0000
136   2   0   1    .0000
138   2   0   1    .0000
141   2   0   1    .0000
168   2   0   1    .0000
170   2   0   1    .0000
172   2   0   1    .0000
174   2   0   1    .0000
176   2   0   1    .0000
185   2   0   1    .0000
```

```
195   2   0   1    .0000
204   2   0   1    .0000
206   2   0   1    .0000
208   2   0   1    .0000
210   2   0   1    .0000
212   2   0   1    .0000
240   2   0   1    .0000
242   2   0   1    .0000
245   2   0   1    .0000
247   2   0   1    .0000
296   2   0   1    .0000
298   2   0   1    .0000
299   2   0   1    .0000
 5   0.0000   0.1000  -0.1944   0.0000
 0   0.1000   2.0000   0.0000  -6.2500
 0   2.0000   3.0000  -6.2500 -11.0000
 0   3.0000  10.0000 -11.0000   0.0000
 0  10.0000  60.0000   0.0000   0.0000
 2   0.0000   1.0000  88.7246  88.6968
 0   1.0000  60.0000  88.6968  88.6968
 4   0.0000   1.0000  88.7246  88.6968
 0   1.0000   1.5000  88.6968  88.0872
 0   1.5000   2.0000  88.0872  87.4776
 0   2.0000  60.0000  87.4776  87.4776
 0
```

APPENDIX C INPUT DATA SET FOR MOFAT SIMULATION

```
SIMULATION OF EIC INFILTRATION IN VERTICAL DIRECTION FOR 10
DAYS
  0   1
  0   1   1   2   2   0
  0 513 560  20  28   0   2  35   0  14
  2   4  28   0
  1   0.0000
  9   5.2800
 14   8.3800
 20  10.0000
   .0000  12.0000  24.0000  36.0000  48.0000  60.0000 61.0000
 62.0000  63.0000  64.0000  65.0000  66.0000  67.0000 68.0000
 69.0000  70.0000  80.0000  90.0000 100.0000 110.0000 120.0000
130.0000 150.0000 170.0000 190.0000 210.0000 230.0000 250.0000
   .1660    .0010    .8190   0.7000  54.3080  54.3080
   .3340    .0030    .7870   0.3500  54.3080   2.2630
   .8570   7.1800   2.4006   1.7140
  3  28    .0000
  1  20   7.3000
 21  40   7.2563
 41  60   7.2175
 61  80   7.1400
 81 100   7.0850
101 120   7.0300
121 140   7.0163
141 160   6.9750
161 180   6.9420
181 200   6.9090
201 220   6.8925
221 240   6.8760
241 260   6.8430
261 280   6.8100
281 300   6.7770
301 320   6.7440
321 340   6.6780
341 360   6.6120
361 380   6.5460
381 400   6.5130
401 420   6.4470
421 440   6.4140
441 460   6.3150
461 480   6.2490
481 500   6.1500
501 520   6.0840
```

```
521  540    6.9850
541  560    6.0000
  3     .0000
 -1    2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  1  1  1  1  1
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
  .00000     .00100  60.00000     .00100   0.50000   1.02000
10.00000
600    4   12    0    .00100    .01000    .01000
   .3000    .5000
  2     .0000   32.0000
  1    1    0
  2    2    0
  3    3    0
  4    4    0
  5    5    0
  6    6    0
  7    7    0
  8    8    0
  9    9    0
```

```
 10   10    0
 11   11    0
 12   12    0
 13   13    0
120    0   14
140    0   14
160    0   14
180    0   14
200    0   14
220    0   14
240    0   14
260    0   14
280    0   14
300    0   14
320    0   14
541    3    0
542    4    0
543    5    0
544    6    0
545    7    0
546    8    0
547    9    0
548   10    0
549   11    0
550   12    0
551   13    0
  1    .0000  130.0000    7.3000    7.3000
  1    .0000  130.0000    6.6400    6.6400
  1    .0000  130.0000    5.9800    5.9800
  1    .0000  130.0000    5.3200    5.3200
  1    .0000  130.0000    4.6600    4.6600
  1    .0000  130.0000    4.0000    4.0000
  1    .0000  130.0000    3.3400    3.3400
  1    .0000  130.0000    2.6800    2.6800
  1    .0000  130.0000    2.0200    2.0200
  1    .0000  130.0000    1.4000    1.4000
  1    .0000  130.0000     .7800     .7800
  1    .0000  130.0000     .1600     .1600
  1    .0000  130.0000     .0000     .0000
  3    .0000    0.0010    0.0500    0.0500
     0.0010   10.0000    0.0500    0.0500
    10.0000  130.0000    0.0500    0.0000
  3    4   10    4
0.000090  1.531300  0.240000  0.000000
0.000090  1.014200  0.280000  0.000000
0.000090  3.281250  0.220000  0.000000
```

```
0.000090  2.625000  0.370000  0.000000
  0.0000    0.0000    0.0000     .0000
  0.0000    0.0000    0.0000     .0000
  0.0000    0.0000    0.0000     .0000
  0.0000    0.0000    0.0000     .0000
  0.4000    0.0500
  0.4000    0.0500
1000.0000  857.0000    1.1000
 879.0000    0.0780
 867.0000    0.0920
 861.0000    0.1060
 867.0000    0.1060
   1    .0000
   1    .0000
   1    .0000
   1    .0000
 114    3    1    2    3    4    0
 133    3    1    2    3    4    0
 152    3    1    2    3    4    0
 171    3    1    2    3    4    0
 190    3    1    2    3    4    0
 209    3    1    2    3    4    0
 228    3    1    2    3    4    0
 247    3    1    2    3    4    0
 266    3    1    2    3    4    0
 285    3    1    2    3    4    0
   1    .0000  130.0000    0.8000    0.8000
   1    .0000  130.0000    4.4000    4.4000
   1    .0000  130.0000    0.8000    0.8000
   1    .0000  130.0000    0.5000    0.5000
```

SIMULATION OF EIC REDISTRIBUTION FOR 30, 60, 90, 120 DAYS

```
   0    1
   0    1    1    2    2    1
   0  513  560   20   28    0    2   24    0   13
   2    4   28    0
   1    0.0000
   9    5.2800
  14     8.3800
  20    10.0000
    .0000   12.0000   24.0000   36.0000   48.0000   60.0000   61.0000
  62.0000   63.0000   64.0000   65.0000   66.0000   67.0000   68.0000
  69.0000   70.0000   80.0000   90.0000  100.0000  110.0000  120.0000
 130.0000  150.0000  170.0000  190.0000  210.0000  230.0000  250.0000
    .1660     .0010     .8190    0.7000   54.3080   54.3080
    .3340     .0030     .7870    0.3500   54.3080    2.2630
    .8570    7.1800    2.4006    1.7140
  -1    2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 1
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2  10.00000    .00100 130.00000
 .00100   0.50000   1.02000  30.00000
```

```
600    4   12    0    .00100    .01000    .01000
  .2000    .5000
 0     .0000   32.0000
 1    1    0
 2    2    0
 3    3    0
 4    4    0
 5    5    0
 6    6    0
 7    7    0
 8    8    0
 9    9    0
10   10    0
11   11    0
12   12    0
13   13    0
541    3    0
542    4    0
543    5    0
544    6    0
545    7    0
546    8    0
547    9    0
548   10    0
549   11    0
550   12    0
551   13    0
  1     .0000  130.0000    7.3000    7.3000
  1     .0000  130.0000    6.6400    6.6400
  1     .0000  130.0000    5.9800    5.9800
  1     .0000  130.0000    5.3200    5.3200
  1     .0000  130.0000    4.6600    4.6600
  1     .0000  130.0000    4.0000    4.0000
  1     .0000  130.0000    3.3400    3.3400
  1     .0000  130.0000    2.6800    2.6800
  1     .0000  130.0000    2.0200    2.0200
  1     .0000  130.0000    1.4000    1.4000
  1     .0000  130.0000     .7800     .7800
  1     .0000  130.0000     .1600     .1600
  1     .0000  130.0000     .0000     .0000
  3    4   10    4
0.000090  1.531300  0.240000  0.000000
0.000090  1.014200  0.280000  0.000000
0.000090  3.281250  0.220000  0.000000
0.000090  2.625000  0.370000  0.000000
  0.0000    0.0000    0.0000     .0000
```

```
  0.0000    0.0000    0.0000      .0000
  0.0000    0.0000    0.0000      .0000
  0.0000    0.0000    0.0000      .0000
  0.5000    0.0500
  0.5000    0.0500
1000.0000  857.0000    1.1000
 879.0000    0.0780
 867.0000    0.0920
 861.0000    0.1060
 867.0000    0.1060
 114   3   1   2   3   4   0
 133   3   1   2   3   4   0
 152   3   1   2   3   4   0
 171   3   1   2   3   4   0
 190   3   1   2   3   4   0
 209   3   1   2   3   4   0
 228   3   1   2   3   4   0
 247   3   1   2   3   4   0
 266   3   1   2   3   4   0
 285   3   1   2   3   4   0
   2   0.0000    0.0010    0.8000    0.0000
   0   0.0010  130.0000    0.0000    0.0000
   2   0.0000    0.0010    4.4000    0.0000
   0   0.0010  130.0000    0.0000    0.0000
   2   0.0000    0.0010    0.5000    0.0000
   0   0.0010  130.0000    0.0000    0.0000
   2   0.0000    0.0010    0.5000    0.0000
   0   0.0010  130.0000    0.0000    0.0000
```

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NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259). This report is available only through NTIS (see address given above).

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NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317).

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NCEER-87-0015 "Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712).

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