PROBABILITY BASED SCREENING GUIDELINES TO ESTIMATE SOIL VENTING REMEDIATION VIABILITY

By

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TO ESTIMATE SOIL VENTING
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INTRODUCTION

Today, state and federal regulatory agencies are increasingly concerned with the impact on human health and the environment resulting from petroleum hydrocarbon products leaked into the unsaturated zone from underground storage tanks (UST) (USEPA 1990). An estimated 95 percent of the 1.4 to 2.0 million UST systems in the United States were used to store petroleum hydrocarbon products. Gasoline was by far the most common product stored and potentially leaked to the subsurface. This conclusion was underscored by the fact that approximately 70 percent of UST leaks reported between 1970 and 1984 involved gasoline (Hartley and Ohanian, 1990).

Based on growing estimates of UST's currently leaking hydrocarbon products, the negative impact of these releases on health and environment is expected to remain high in the future. Up to 20 percent of the UST's in use in the United States today may be releasing as much as 11 million gallons of gasoline to the subsurface each year (Bouchard, et al., 1990). In addition, it is believed that approximately 25 percent of the estimated one million above-ground petroleum storage tanks are also leaking (McCray, 1993). Current opinion indicates that after detection rapid cleanup of gasoline spills in the unsaturated zone should be a key objective in the overall remediation strategy. Capture of gasoline products in the unsaturated zone prevents their migration to underlying fresh water aquifers, simplifying cleanup and reducing risk to human health and the environment. To that end, soil vapor extraction, or soil venting, has become a widely used and accepted method for removing hydrocarbon contamination from unsaturated soils

(Gierke et al., 1992).

The technology of soil venting systems has been available for about twenty years and the essential ideas controlling its operation and effectiveness are well understood (Shan et al.; 1992). Earlier versions of soil venting systems which were used to passively vent landfills were subsequently modified to induce more airflow through contaminated regions and improve performance. The technology steadily gained popularity through the 1980's and has been extensively utilized to successfully remediate gasoline and some semi-volatile chemical spills from UST's and large diameter (150 ft.) above-ground storage tanks. Additional applications of soil venting in remediating larger and more chemically diverse Superfund sites were started in 1988 (USEPA, 1991a). Increasing detection of past and present hydrocarbon leaks suggests that soil venting will continue as the treatment of choice for remediating hydrocarbon contaminated soils. Certainty of future hydrocarbon leaks and the EPA's growing acceptance of the use of soil venting technology at Superfund sites will ensure that soil venting continues as the predominant remediation choice for cleanup of the unsaturated zone.

The basic forced air soil venting system (Figure 1) involves placing air injection wells around the perimeter of the contaminated zone. Air flows from these wells and passes through the soil, volatilizing liquid phase (and other phases, if present) contaminants. Gases generated from the volatilized liquid fill the open pore spaces within the unsaturated zone. A vacuum is applied to extraction wells located within the zone of contamination and the gases are removed. Depending on local ordinances, the gases are either emitted directly to the atmosphere or treated to reduce contaminant concentrations prior to emission. The soil venting process continues until all condensed and gaseous phases are removed. A surface covering of impermeable earthen or man-made material is usually placed over the vented area to prevent loss of vacuum to the atmosphere through the ground-surface. Numerous papers and case studies have been published documenting the merits and effectiveness of vapor extraction in varying geologic and chemical regimes.

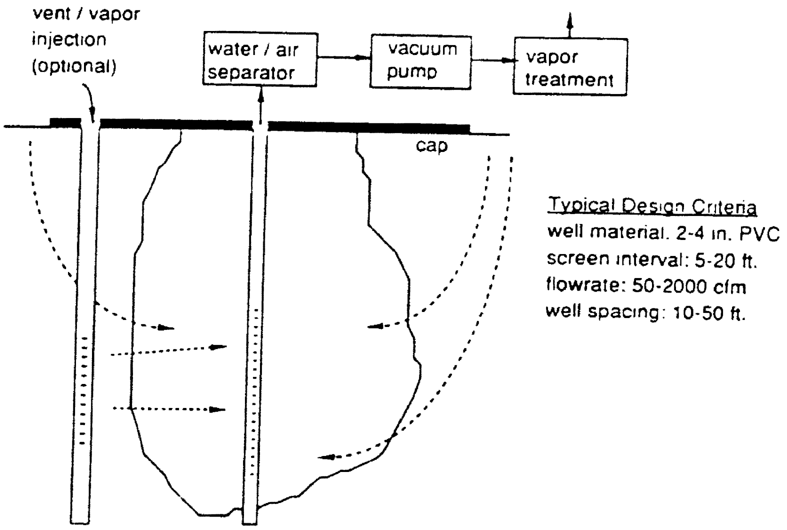


Figure 1. Typical soil venting system (after Rathfelder et. al.; 1991)

Many have been reviewed by Hutzler et al., (1989); Pederson and Curtis (1991); and EPA (1989) and (1989a). Following several years of research and analysis of field applications, the merits of soil venting have become evident: 1) the soil is treated in place, 2) elaborate equipment is not required, 3) set-up is quick and operations are relatively easy, and 4) when properly applied, cost savings can be significant in comparison to other remediation options (Pederson and Curtis, 1991). However, if the process is not properly applied, the cost savings associated with soil venting may be quickly lost due to protracted remediation times or the inability to comply with cleanup standards.

In the past, there have been few guidelines to assist the engineer in determining optimum venting applications and system design (Gierke et al.; 1989, Shan et al; 1992). Recent development of a variety of numerical codes has provided the means to screen and design soil venting systems for a range of field conditions and for varying parameter selections (Johnson et al., 1990 and 1990a; Rathfelder et al., 1991; Marley et al.; 1990; Massmann, 1989). Predictive numerical models such as these rely on solving expressions for induced advective air flow and contaminant mass transport. These models also provided a means to investigate the sensitivity of parameters that control site-specific soil venting efficiency (Rathfelder et al.; 1991). Results of these investigations generally indicated that the key factors in venting performance were air flow and mass removal rates (Feenstra and Hennet, 1993). More specifically, Johnson et al. (1990) found that the largest uncertainty in air flow calculations was caused by variations in a soil's air permeability ranging up to three orders of magnitude. Similar findings were reported by Rathfelder et al. (1991), who developed a two-dimensional model to simulate hypothetical field scale venting problems. Using varied, non-associated (with soil type) permeability values, they demonstrated that the efficiency of venting is highly sensitive to the magnitude and distribution of soil permeability. These and other studies (i.e., Stephanatos, 1990; Marley et al.; 1990) have demonstrated a strong correlation between venting efficiency and permeability. Thus the type of soils or soil textural class present at a site becomes a major design and decision-making parameter when considering soil venting remediation (Baehr et al.; 1989).

Regardless of a model's sophistication, an initial estimate of soil air permeability must be provided by the user in order to calculate air flow rates and compute mass removal rates. Due to extreme variability of soil parameters, making adequate estimates of air permeability is often difficult without costly specialized lab or field testing. The most common approach recommended for estimating air permeability is in-situ pumping tests (Johnson et al., 1990) which go beyond the preliminary screening level. In the absence of suitable specific field data, estimating this parameter can lead to significant uncertainty of model results. Therefore the application of venting models as preliminary screening tools is limited by the amount of site specific permeability data that is available.

Parallel efforts have been made by researchers engaged in research with an agricultural and soils focus to define permeability relationships based upon primary soil properties (i.e. Carsel and Parrish, 1988; van Genuchten, 1980 and 1991; and Rawls and Brankensiek, 1985). The ability to infer a soil's air permeability from its physical properties offers an alternative to currently used field methods and can be applied to the development of screening guidelines. From that research, a model to accurately predict the key soil parameters necessary to calculate air permeability and a method to predict the frequency and magnitude of those parameters have been joined with a numerical soil venting model to predict the efficiency of soil venting without conducting field tests.

Research Objective

The purpose of this study was to employ currently available statistical and mathematical techniques to develop a probability-based nomograph to define the potential efficacy of soil venting over a range of soil, spill, and operational conditions. Drawing upon agricultural soils research, Monte Carlo methods were used to address parameter uncertainty and assess the magnitude and frequency of air permeability in four common soil textures. A series of hypothetical remediation simulations were run using a publicly available numerical model to evaluate the performance of soil venting within each soil class using the calculated permeabilities. Once developed the nomographs will serve as a preliminary screening tool to be applied before modeling to determine potential contaminant removal efficiencies for typical gasoline spills associated with UST's. In this manner, a tool would be available for preliminary design which addressed parameter uncertainty in estimating air permeability that did not require site specific data other than soil texture classification.

The nomograph and tables will allow users to assess the probability of success in terms of treatment (venting) times needed to achieve regulatory requirements (% recovery of contaminants). Probabilities of reaching an acceptable state or federally defined soil concentration within a specific timeframe could be determined for the individual gasoline components followed in this study or for soil total hydrocarbon concentration (TPH).

Based on the strength of the probability estimates, potential candidates for soil venting could be screened for direct implementation, further study and testing, or elimination from consideration. If user-defined probability of success was high enough, continued testing could be bypassed and actual cleanup operations initiated. Conversely, low probabilities would indicate that additional field data and testing for the express purpose of further consideration of soil venting is not warranted. At this point remedial alternatives should be considered, thereby avoiding pointless testing and saving considerable time and money.

PROCESS BACKGROUND

Determination of Critical Soil and Operational Variables

There are several computer codes available either in the public domain or through proprietary sources that can be employed to assist the engineer in the design of these systems (Rathfelder et al.; 1991). These models were developed to predict and quantify vapor flow rates and contaminant mass transport in soil. Typically these models are based on numerical solutions of the governing mass balance and radial flow equations and are subject to several simplifying assumptions. Analysis of these equations would indicate which variables would have the most impact upon the simulation output.

Air Flow Rate

Equation 1 presents an analytical one-dimensional radial gas flow model that is a commonly accepted design basis employed in many of these codes to estimate air flow rates. Changes in the vapor-filled porosity caused by liquid removal which ultimately impacts relative permeability are neglected in equation 1 because the effects are negligible for soils with less than 20 percent water content (Johnson et al.; 1990a). This is justified given that average water content for sand and sandy soils is less than 20 percent. Equation 1 further assumes that the vapor behaves as an ideal gas.

$$Q = \pi H \frac{k_a}{\mu} P_w \frac{[1-(P_{atm}/P_w)^2]}{\ln(R_w/R_I)} \qquad (1)$$

where:

k_a = soil air permeability (darcy)
μ = viscosity of air = 0.018 cp
P_W = absolute pressure (vacuum) at extraction well (atm)
P_{atm} = absolute ambient pressure (taken as 1 atm)
R_W = radius of vapor extraction well (in)
R_I = radius of influence of vapor extraction well (ft)
H = height of well screen (ft)

The parameters in equation (1) define the key variables that control the rate of air flow through the contaminant zone. Air flow rate can be seen as a function of soil air permeability and operating parameters related to system design considerations. System variables such as extraction well bore radius and vacuum can be incrementally adjusted by the operator within narrow pre-defined ranges to enhance flow rates.

Extraction well radius of influence (ROI) is a measure of the radial propagation of the subsurface vacuum which is applied. Theoretically it is a function of soil type where highly permeable soils have larger ROI's than less permeable soils. Estimates of ROI range from 15 feet to over 100 feet for sandy soils (Pederson and Curtis, 1990). However, under actual field conditions vacuum propagation and ensuing air velocity were found to decrease substantially with distance from an extraction well which implied that ROI was not an effective parameter for locating extraction wells (DiGiulio et al.; 1990). Therefore, ROI was conservatively estimated at 30 feet, despite previous literature estimates, on the basis that only a limited volume of soil near an extraction well would be effectively ventilated and held fixed for all soil types.

The most critical and uncertain variable in the air flow equation is horizontal air permeability. It can be viewed as a random variable because the operator has no control over its value. The soils literature contains numerous assessments documenting the spatial variability of hydraulic properties and permeability with textural characteristics of soils (e.g. Russo and Dagan, 1993; Unlu et al.; 1990, Parkin et al.; 1988). Permeability is by far the most uncertain and variable soil parameter. Depending on textural content, its absolute value can range widely over more than 10 orders of magnitude (Massmann, 1989). Typical ranges of soil intrinsic permeability and hydraulic conductivity by soil types or material are shown in Table 1. Comparing the range of permeability values in Table 1, each soil type may have a permeability which can range over two to four orders of magnitude. In addition significant overlap of permeability values between soil types can be seen. Given the wide-ranging continuum of permeability values, the same value could be estimated for three different soil types. Because most permeability guidelines tend to be very general as shown in Table 1, significant uncertainty is introduced when permeability values are estimated from the literature for input into numerical models to

TABLE 1. Typical ranges of hydraulic conductivity and permeability values for soil.

Soil Type	Range of Intrinsic Permeability (darcy)	Range of Hydraulic Conductivity (cm/sec)
Gravel	10^{1}- 10^{3}	10^{-2} - 10^{0}
Sand, glacial outwash	10^{0} - 10^{2}	10^{-3}- 10^{-1}
Loam, silty sand	10^{-2} - 10^{2}	10^{-5} - 10^{-1}
Silt, sandy silt	10^{-3} - 10^{1}	10^{-6} - 10^{-3}
Clay	10^{-6} - 10^{-3}	10^{-9} - 10^{-6}

Source: After USEPA (1990), Massmann (1989), and Fetter (1988) evaluate potential venting applications.

Mass Removal Rate

The rate of contaminant removal is usually determined by a calculated molar mass balance for each chemical component completed over a series of user defined venting time steps according to equation 2:

$$\frac{dM_i}{dt} = -\eta Q C_i^{eq} \tag{2}$$

where:

M_i = total number of moles of component i in the soil (mole)
Q = total gas flow rate through the contaminated zone (L^3/T)
C_i^{eq} = equilibrium molar gas phase concentration of species i (mole/L^3)
η = efficiency factor to account for nonequilibrium effects (unitless)

Mass removal rates are calculated by equation 2 assuming that the contaminant is uniformly distributed throughout a given amount of soil at all times and vapor free-liquid, sorbed and dissolved phases are always in equilibrium. This equation shows that the change in the contaminant mass of any component over time is a function of air flow rate, spill size, and gas phase concentration (which is directly related to volatility of the component). The greater the air flow rate passing through the contaminated soil, the greater the contaminant mass removal rate. The rate of mass removal in turn controls the length of time required to reduce the contaminant mass to meet cleanup goals. In turn, air flow rates are controlled by intrinsic permeability of the soil, its water content, and the amount of air filled porosity. Since air flow through the soil is mainly controlled by permeability and mass removal rates are in turn primarily controlled by air flow, the soil's air permeability becomes a critical design factor, varying with soil type and moisture content. The efficiency factor defines the ratio of actual gas phase concentration entering the well to the concentration that would occur if all air flow passes through the contaminated soil zone.

The direct impact of air permeability can be readily seen in equation (1). Air permeability could vary by several orders of magnitude within any one soil type. Other variables in the air flow equation varied by much less than one order of magnitude. Most venting models treat permeability as a single fixed value for calculation of air flow. More recent models (Benson et al.; 1993, Sepehr and Samani, 1993) are able to recalculate initial air permeability and porosity values to account for changing soil moisture in the simulation. However, regardless of the type of numerical model used in the screening or modeling process, uncertainty is introduced when arbitrarily selecting a single estimate of soil air permeability that could vary by four orders of magnitude for any soil type. Potential success of soil venting could easily be greatly under- or over-estimated. Uncertainty could be reduced if the range and frequency of occurrence of permeability data are considered.

RESEARCH STRUCTURE

The subject research focused upon the development of a probability based screening tool which utilized randomly generated soil properties to calculate an expected range of air permeabilities. Which then could be used in deterministic venting models to evaluate venting efficiencies. Evaluation of soil venting applicability was centered around soil textural classes and key system or management variables (referred to as incremental variables). Incremental variables, as determined from equations (1) and (2) are those parameters, other than air permeability which may have a pronounced effect on venting efficiencies. These were determined to be extraction vacuum, spill size and contamiante zone thickness. Taken together these incremental variables attempted to simulate a variety of conditions in which soil venting may be used as well as be representative of actual site parameters. Thus each combination of incremental variables defines a different scenario for which venting efficiency was measured.

For each scenario or simulation evaluated the incremental variables were held fixed as a range of probability defined air permeabilities were sequentially input to evaluate venting efficiency for that set of conditions defined by the incremental variables. For the next simulation one incremental value was adjusted while the others remain fixed. Thus, the process continued until all possible combinations of incremental values have been simulated.

Modeling the soil venting process involved the selection of a number of other non random variables. These variables were held at fixed values throughout the study because they either had very little impact on the model output or had a minimal range of variance. A summary of data requirements to run the venting program is shown in Table 2.

For this study, it was assumed that venting efficiency was 100 percent. This requires that the venting well's screened interval corresponds to contaminant thickness, thus allowing all air flow to pass through only contaminated soil. It is further assumed any free product is removed prior to soil venting and that no mass transfer limitations exist due to diffusion limited processes or incomplete contact with the contaminated soil zone. Although 100% efficiency of soil venting is not likely in all applications, it was assumed as such so that a common basis of comparison between the soils was established.

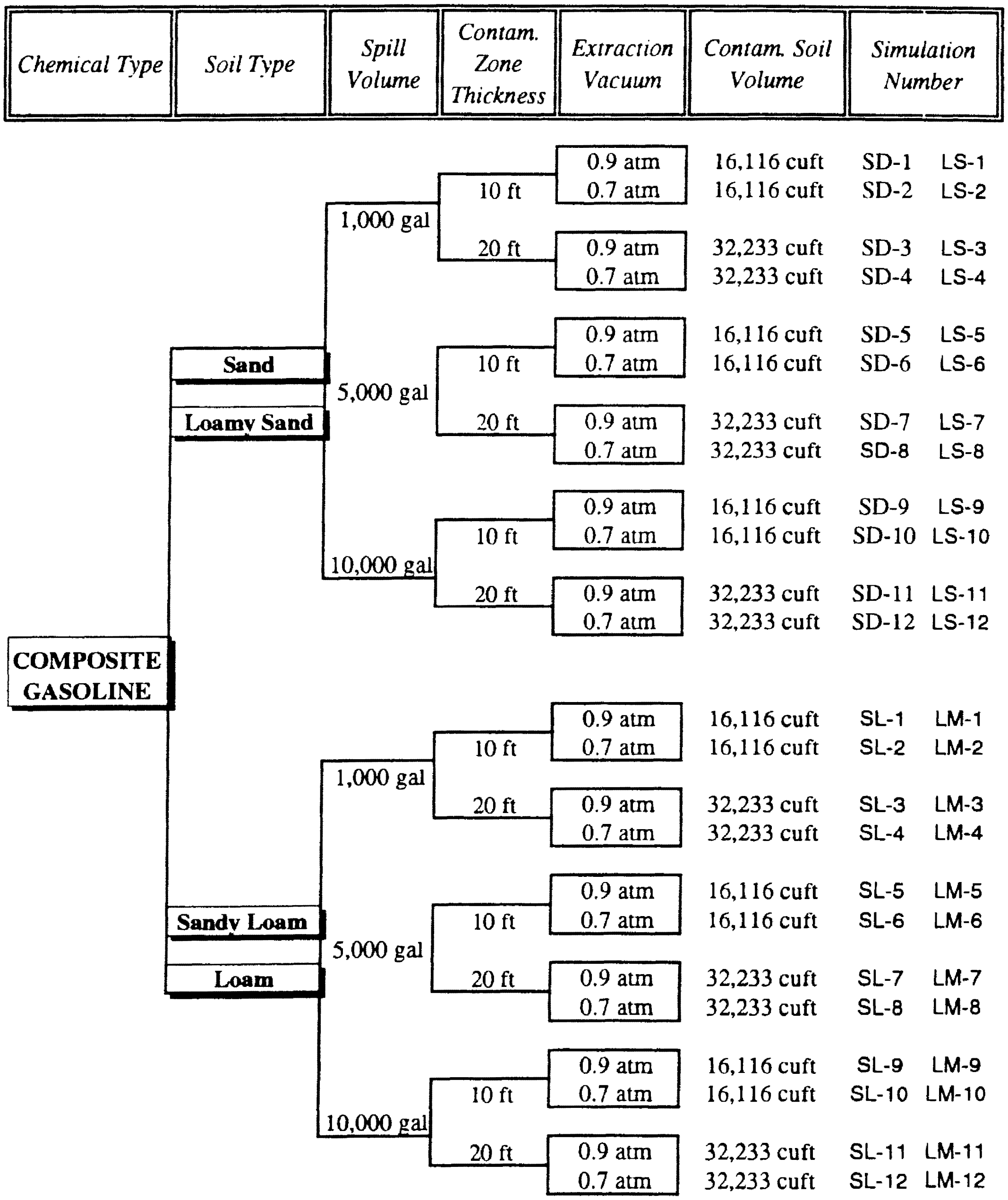
A range of probability defined air permeabilities for each soil type were used in the soil venting model in conjunction with incremental or step-wise descriptions of contaminant spill volume, thickness, and pressure drop (extraction vacuum) to produce probability curves representing total petroleum hydrocarbon (TPH) and select constituent expected recoveries from a typical gasoline spill in the subsurface. These probability curves were generated by soil textural class for four different soil types, varying from sand through sandy loam and loamy sand to loam. As will be discussed in a later section, these soils differed mainly in sand and clay content that make up each. Thus the design engineer need only know the soil texture and spill size (in terms of volume) to access these curves, generating a prediction of the overall probability of success (defined by percent recovery of the TPH and/or individual constituents) for any given site. Additional disaggregation or re-grouping of the data sets was accomplished allowing a comparison of the effects of spill size, contaminated zone thickness, and extraction vacuum for each of the performance criteria. An interpolation technique using the disaggregated data sets is presented which allows intermediate values of incremental variables to be used in the analysis of venting efficiency. Figure 2 presents the overall research structure used in this effort.

To complete the stated objectives and meet research goals, the study was divided into three major steps:

1) Perform Monte Carlo analysis of soil air permeability by soil textural class: a) repeatedly generate correlated sets of randomized soil parameters; b) calculate soil air permeability; c) perform distribution and probability evaluation of permeability data; d) determine probability of occurrence of air permeability values based on overall distribution within each soil class.
2) Determine efficiency of soil venting as a function of soil class: 1) Input probability indexed soil air permeability values to a numerical code to model contaminant recovery of hypothetical gasoline spill; 2) repeat model simulations over a range of operating conditions for each soil class.
3) Determine probability of venting success from model output: a:) construct probability plots of overall percent recovery versus time for selected individual gasoline component concentrations and TPH for each soil class; b) assess impact of selected operational variables by replotting disaggregated probability data by soil class.

Detailed discussion of each step is presented in the following sections.

Figure 2. Flow chart showing research structure and overall range of spill site variables.



Chemical Type	*Soil Type*	*Spill Volume*	*Contam. Zone Thickness*	*Extraction Vacuum*	*Contam. Soil Volume*	*Simulation Number*	
COMPOSITE GASOLINE	**Sand** **Loamy Sand**	1,000 gal	10 ft	0.9 atm	16,116 cuft	SD-1	LS-1
				0.7 atm	16,116 cuft	SD-2	LS-2
			20 ft	0.9 atm	32,233 cuft	SD-3	LS-3
				0.7 atm	32,233 cuft	SD-4	LS-4
		5,000 gal	10 ft	0.9 atm	16,116 cuft	SD-5	LS-5
				0.7 atm	16,116 cuft	SD-6	LS-6
			20 ft	0.9 atm	32,233 cuft	SD-7	LS-7
				0.7 atm	32,233 cuft	SD-8	LS-8
		10,000 gal	10 ft	0.9 atm	16,116 cuft	SD-9	LS-9
				0.7 atm	16,116 cuft	SD-10	LS-10
			20 ft	0.9 atm	32,233 cuft	SD-11	LS-11
				0.7 atm	32,233 cuft	SD-12	LS-12
	Sandy Loam **Loam**	1,000 gal	10 ft	0.9 atm	16,116 cuft	SL-1	LM-1
				0.7 atm	16,116 cuft	SL-2	LM-2
			20 ft	0.9 atm	32,233 cuft	SL-3	LM-3
				0.7 atm	32,233 cuft	SL-4	LM-4
		5,000 gal	10 ft	0.9 atm	16,116 cuft	SL-5	LM-5
				0.7 atm	16,116 cuft	SL-6	LM-6
			20 ft	0.9 atm	32,233 cuft	SL-7	LM-7
				0.7 atm	32,233 cuft	SL-8	LM-8
		10,000 gal	10 ft	0.9 atm	16,116 cuft	SL-9	LM-9
				0.7 atm	16,116 cuft	SL-10	LM-10
			20 ft	0.9 atm	32,233 cuft	SL-11	LM-11
				0.7 atm	32,233 cuft	SL-12	LM-12

SD - sand
SL - sandy loam
LS - loamy sand
LM - loam

MONTE CARLO SIMULATION

Stochastic Modeling

Stochastic modeling considers the chance occurrence of variables and uses the idea of probability to describe the occurrence of those variables (Chow, 1964). A common approach to stochastic evaluation of random processes is the Monte Carlo simulation method. This approach involves repeatedly solving a deterministic model or single-valued problem using inputs generated randomly from specific probability distributions. A distribution of model outputs is obtained which can be viewed as plausible representations of "reality" over the entire range of possible outcomes. When input parameters are conditionally simulated on observed data and have the same mean and variance of actual measurements, further accuracy is obtained and the full range of data uncertainty is addressed.

Stochastic methods have been used to describe hydraulic conductivity in the analysis of groundwater flow for more than a decade (Varljen and Shafer, 1991). Recent unsaturated zone examples include that of Assaid and Hess (1993) who used Monte Carlo methods to simulate oil infiltration in a hypothetical glacial outwash. Carsel et al. (1988 and 1988a) used Monte Carlo simulation based on nationwide distributions of soil properties to investigate pesticide leaching in the unsaturated zone. However, few if any applications have been demonstrated for analyzing hydrocarbon recovery from the unsaturated zone using soil venting extraction technology. Pederson and Curtis (1991) constructed a simple nomograph in terms of the soil's air permeability to vapor flow, contaminant vapor pressure, and the time of release to predict the likelihood of success of a soil venting system. However, probability of success was scaled in non-quantitative terms. While informative in the general sense, it did not address remediation time because spill size variations were not considered. Johnson et al. (1990) considered the effect of varying air permeability on air flow rates and concluded that to be prudent, air flow rates should be repeatedly calculated using permeabilites over a range of two orders of magnitude. The lack of practical stochastic studies of soil venting is due in part to the relatively recent development of appropriate numerical models describing air flow.

Application of Monte Carlo Analysis to Soil Air Permeability

In this study, a Monte Carlo approach was used to evaluate the range and occurrence of soil air permeability. It was based on the premise that for any given site, soil properties overwhelmingly control venting efficiency and that specific soil type or soil textural data is almost always available (USEPA, 1990; specific sources include public works departments, Geological Survey, and Department of Agriculture Soil Conservation Service). The basis of any Monte Carlo simulation is to numerically generate (simulate) many realizations of the random variable for input into a deterministic model. Frequency distributions were used to express the magnitude and occurrence of air permeability as probabilities of occurrence within each soil class. Selected air permeability data from various probability levels were input in a soil vapor extraction model to determine the effectiveness of hydrocarbon removal for a variety of field and operational scenarios within each soil class according to Figure 2.

Given the probability distribution of the resulting air permeabilities, one could assign the same probability to the model output. This is explained by the fact that air permeability was the only input parameter treated as a random variable for every simulation. All other parameters were held constant for the course of each simulation and were then incrementally adjusted for the next simulation or held constant throughout. As previously discussed, air permeability was chosen as the single random variable to be modeled because soil air permeability is the most highly variable and uncertain parameter required by many of the numerical models. It is also the primary factor in determining air flow rate which in turn determines the rate of hydrocarbon recovery.

DEVELOPMENT OF SOIL DATA AND PERMEABILITY ESTIMATIONS

Introduction

Monte Carlo simulation methods require probability density functions which describe actual or inferred distributions of input parameters in order to generate random values. One method of estimating probability density functions for soil-saturated hydraulic conductivity and other hydraulic parameters was developed by Carsel and Parrish (1988). Their method employed a multiple regression equation for estimating water content at a given pressure head and saturated hydraulic conductivity using the saturated water content and the percentages of sand and clay present in a soil. The methodology was developed as part of a study that used Monte Carlo techniques requiring distributional and correlational information to evaluate solute transport and leaching potential of pesticides in agricultural soils. In that assessment, (Carsel et al.; 1988) estimated distributions of field capacity and wilting point from national soil distributions. These were used to characterize input parameters for the Pesticide Root Zone Model (PRZM). The assessment technique and probability density functions described in that study could be adapted for use with other unsaturated zone models which require soil parameter input data (Carsel et. al.; 1988). Since the parameters necessary to calculate soil air permeability could be obtained in this manner, the method was adopted for use in this study. Because the procedures developed by Carsel and Parrish (1988) to randomly generate correlated soil properties is a crucial part of this study a detailed overview of the major steps in the procedure are summarized in the following discussion.

Generation of Random Soil Parameters

Rawls and Brakensiek (1985) developed a multiple regression method for estimating saturated hydraulic conductivity as well as other parameters required by several water retention models from soil-saturated water content, sand content, and clay content. Their method was the basis upon which Carsel and Parrish (1988) inferred probability distributions of soil parameters from a large parent set of actual field measurements of soil data. Using the observed statistical distributions of soil parameters derived from utilization of the Rawls and Brakensiek (1985) multiple regression equation, they developed a method to generate random values of the soil parameters. Additionally, Carsel and Parrish (1988) developed correlations among the predicted sets of soil parameters for various soil textural classes which served to better represent the actual relative frequency of the variables studied.

Carsel and Parrish (1988) assembled a soil database consisting of bulk density, sand, and clay contents for 12 Soil Conservation Service (SCS) textural classifications. The soil data were compiled from a nationwide distribution of soils from 42 states. Descriptive statistics for percent sand and clay content for all soils which indicate the range of textural properties (except silt fraction which was not reported) and served as the basis for textural classifications, are shown in Table 3. From these 12 soil classifications, four soils including sand, sandy loam, loamy sand, and loam were selected for analysis in the present study. These four soil types were selected because they represented the broadest range of sand and clay contents and had an average hydraulic conductivity of more than one cm/hr. Average sand content of the four soils included in this study ranged from 93 percent in the sand classification to 40 percent in the loam classification. Technically speaking loam does not describe a soil texture, rather it is used by the SCS to describe a soil with a relatively even mixture of different grades of sand, silt and clay size fractions.

TABLE 3. Range of Textural Properties and Hydraulic Conductivity by SCS Soil Classification.

SOIL TYPE	Max % Sand	Min % Sand	Mean % Sand	Max % Clay	Min % Clay	Mean % Clay	Mean Hyd. Cond. (cm/hr)
Sand*	100	85	93	10	0	3	29.70
Loamy sand*	90	70	81	15	0	6	14.59
Sandy loam*	85	45	63	20	0	11	4.42
Sandy clay loam	80	45	54	35	20	27	1.31
Sandy clay	65	45	48	55	35	41	0.12
Loam*	50	25	40	28	8	20	1.04
Silt loam	50	0	17	28	0	19	0.45
Silty clay loam	20	0	8	55	35	33	0.07
Silty clay	20	0	7	60	40	46	0.02

* indicates soil class included in this study
Source: Carsel and Parrish (1988)

The SCS database individually reported saturated water content (inferred from bulk density) and sand and clay contents for each soil class. From these data saturated hydraulic conductivity (K_S), residual water content (Θ_r), and van Genuchten water retention parameters alpha (α) and N were computed using the multiple regression equation developed by Rawls and Brakensiek (Figure 3).

Term	ln (KS)	θr	ln (α^{-1})	ln (N−1)
(Constant)	−8.96847	−0.0182482	5.3396738	−0.7842831
S	–	0.0087269	–	0.0177544
C	−0.028212	0.00513488	0.1845038	–
θ_s	19.52348	0.02939286	−2.48394546	−1.062498
S^2	0.00018107	–	–	−0.00005304
C^2	−0.0094125	−0.0015395	−0.00213853	−0.00273493
θ_s^2	−8.395215	–	–	1.11134946
SC	–	–	–	–
$S\theta_s$	0.077718	−0.0010827	−0.0435649	−0.03088295
$C\theta_s$	–	–	−0.61745089	–
S^2C	0.0000173	–	−0.00001282	−0.00000235
$C^2\theta_s$	0.02733	0.0030703	0.00895359	0.00798746
$S^2\theta_s$	0.001434	–	−0.0072472	–
SC_2	−0.0000035	–	0.0000054	–
$C\theta_s^2$	–	−0.0023584	0.50028060	−0.00674491
$S^2\theta_s^2$	−0.00298	–	0.00143598	0.00026587
$C^2\theta_s^2$	−0.019492	−0.0018233	−0.00855375	−0.00610522

S = percent sand ($5<S<70$)
C = percent clay ($5<C<60$)
θ_s = total saturated water content, cm ^{3} cm^{-3}
KS = saturated hydraulic conductivity, cm hr^{-1}
θ_r = residual water content, cm ^{3} cm^{-3}
α = empirical constant, cm^{-1}
N = empirical constant

General regression model:

$$\begin{aligned} f(S,C,\theta_s) = [&b_0 + b_1 S + b_2 C + b_3\theta_s + b_{11} S^2 + b_{22} C^2 + b_{33}\theta_s^2 \\ &+ b_{12} SC + b_{13} S\theta_s + b_{23} C\theta_s \\ &+ b_{112} S^2C + b_{223} C^2\theta_s + b_{113} S^2\theta_s + b_{122} SC^2 \\ &+ b_{233} C\theta_s^2 + b_{1133} S^2\theta_s^2 + b_{2233} C^2\theta_s^2] \end{aligned}$$

Figure 3. Rawls and Brakensiek (1985) multiple regression model used by Carsel and Parrish (1988) to estimate selected soil water retention parameters.

The general form of the regression equation and related coefficients are shown in Figure 3, where f denotes any of the variables ln (K_S), (Θ_r), ln (α^{-1}), or ln (N-1). Water retention parameters predicted with the regression equation were used in the van Genuchten (1980) model to predict soil water content as a function of pressure head. The work of Rawls and Brakensiek (1985) included testing of their regression model using 95 soils with textural classifications ranging from clays to sands. Estimated means for final infiltration rates were within one standard deviation of the observed means. Generally, predictive models such as this one have been found to work well for many coarser-textured soils (van Genuchten et al.; 1990). The main advantages to using the regression equation were that spatial representations of hydraulic parameters could be estimated from expected variations of percent sand and clay content within each soil class. And, since these data were being used to develop screening criteria to cover a range of soils it provided the only viable means (other than direct measurement) of characterizing the hydraulic properties over large and texturally diverse areas.

The resulting database of computed saturated and residual water contents and van Genuchten parameters served as the basis for characterization of probability distributions for these variables. In order to preserve the correlation structure among the four variables to be generated, their joint distribution must be normal. Thus, in every case a mathematical transformation was applied to the data sets which would produce normally distributed variables (Carsel and Parrish, 1988). This was accomplished using a class of transformed normal distributions known as the Johnson system (Johnson and Kotz, 1970).

The Johnson system involved three main distribution types: LN, lognormal; SB, log ratio; and SU, hyperbolic arcsine. Although each will produce normal distributions after the transforms are applied, one usually works better than the others. The underlying reason for this is related to the skewness and kurtosis of the specific data set being transformed (Carsel and Parrish, 1988). For any given case, the transformation that did the best job of producing normally distributed data based on an objective measure of goodness of fit was selected.

Transformations were applied to variables with limits of variation from A to B ($A < X < B$) which corresponded to maximum and minimum values of the untransformed variable denoted as X. The limits of variation (A and B) for each variable were determined on the basis of observed data ranges and theoretical considerations (Carsel and Parrish, 1988). In this manner parameter values were constrained to values that reflected only true field conditions. Estimates of the sample distribution means and standard deviations of the transformed variable and limits of variation for the original variables for the soil classes considered in this study are shown in Table 4.

As can be seen from Table 4, many of the data sets were significantly better described by the SB and SU distributions. For the 12 soil classes in the Carsel and Parrish (1988) study, lognormal transformations were used in about one third of the cases, while SB and SU normal transformations were used in the others. Similarly, for the four soils considered in this study the lognormal transformation was used in only less than one fourth of the cases. Considering the large size of the parent data set from which these data were generated, these results may indicate that applying the commonly used lognormal distribution for estimating soil parameters may not be a valid assumption in all cases.

Table 4. Statistical parameters used for distribution approximations.

		Limits of Variation			Est. Transform Variables	
Soil Texture	Hydraulic Variable	A	B	Trans-formation	Mean	Standard Deviation
S	K_S	0	70	SB	-0.394	1.15
S	Θ_r	0	0.1	LN	-3.12	0.224
S	α	0	0.25	SB	0.378	0.439
S	N	1.5	4.0	LN	0.978	0.100
SL	K_S	0	30	SB	-2.49	1.53
SL	Θ_r	0	0.11	SB	0.384	0.70
SL	α	0	0.25	SB	-0.937	0.764
SL	N	1.35	3.0	LN	0.634	0.082
LS	K_S	0	51	SB	-1.27	1.4
LS	Θ_r	0	0.11	SB	0.075	0.567
LS	α	0	0.25	NO	0.124	0.043
LS	N	1.35	5.0	SB	-1.11	0.307
L	K_S	0	15	SB	-3.71	1.78
L	Θ_r	0	0.12	SB	0.639	0.487
L	α	0	0.15	SB	-1.27	0.786
L	N	1	2	SU	0.532	0.99

Source: Carsel and Parrish (1988)
S, sand; SL, sandy loam; LS, loamy sand; L, loam

After choosing the best fitting distribution, sample covariances and correlations among the transformed variables were computed. These served to estimate the covariances needed to generate a set of normally distributed variables. The distribution was parameterized in terms of marginal distribution means and variances and pairwise covariances in the form of a covariance matrix for each soil class (Table 5). The italicized entries represent sample Pearson product-moment correlations of the variables. In most cases correlations between the van Genuchten parameters and saturated hydraulic conductivity were significant (> 0.70) indicating a strong statistical link. The presence of these correlations implies that some combinations of values are either more or less probable than if no correlation existed (Carsel and Parrish, 1988).

Table 5. Correlations among transformed variables presented with the factored covariance matrix.

	K_S	Θ_r	α	N
Sand (n = 237)				
K_S	1.04	-0.109	0.328	0.081
Θ_r	*-0.515*	0.182	0.258	-0.040
α	*0.743*	*0.119*	0.143	-0.011
N	*0.843*	*-0.858*	*0.298*	0.017
Sandy Loam (n = 1145)				
K_S	1.60	-0.153	0.037	0.211
Θ_r	*-0.237*	0.538	0.017	-0.194
α	*0.856*	*0.151*	0.014	0.019
N	*0.686*	*-0.796*	*0.354*	0.108
Loamy Sand (n = 313)				
K_S	1.48	-0.201	0.037	0.211
Θ_r	*-0.359*	0.522	0.017	0.194
α	*0.986*	*-0.301*	0.014	0.019
N	*0.730*	*-0590*	*0.354*	0.108
Loam (n = 664)				
K_S	1.41	-0.100	0.611	0.055
Θ_r	*0.204*	0.478	0.073	-0.055
α	*0.982*	*-0.086*	0.093	0.026
N	*0.632*	*-0.748*	*0.591*	0.029

Source: Carsel and Parrish, (1988)
Italicized entries are sample Pearson product-moment correlations.
n = original sample size

To produce sets of correlated normal random variables, a random number seed was introduced which in turn generated a set of independent standard normal deviates according to the particular covariance matrix. These random values were then inverse-transformed, depending on the fitted distribution (i.e. SU, SB, or LN) to produce random values for the soil water retention parameters.

The steps involved in generating random variables for the 12 soil textural classes were compiled in a BASIC program written by Carsel and Parrish (see example in Appendix A). Substitution of the appropriate values from Tables 4 and 5 for each soil class was performed to generate random variables. In this manner the soil parameters necessary to calculate soil air permeabilites for this study were obtained. Output consisted of sets of randomly generated, conditionally correlated soil hydraulic properties of saturated hydraulic conductivities (K_S), residual water content (Θ_r), and van Genuchten water retention parameters (α, N) for the soil class specified. In an analysis of their procedure, Carsel and Parrish (1988) generated a 1000 sets of silt loam data and compared them with the original observed data in a series of histograms (Figure 4). Close agreement in terms of the shape of the overall distributions and in the relative frequencies of the individual classes which varied by only a few percent were found between the original observed data and the random values generated using the procedures outlined above. For this study, a total of 720 sets of hydraulic properties were generated using the BASIC program for each soil class. These data were then taken into an EXCEL (Microsoft, 1990) spreadsheet and based on the following discussion, used to calculate soil air permeability.

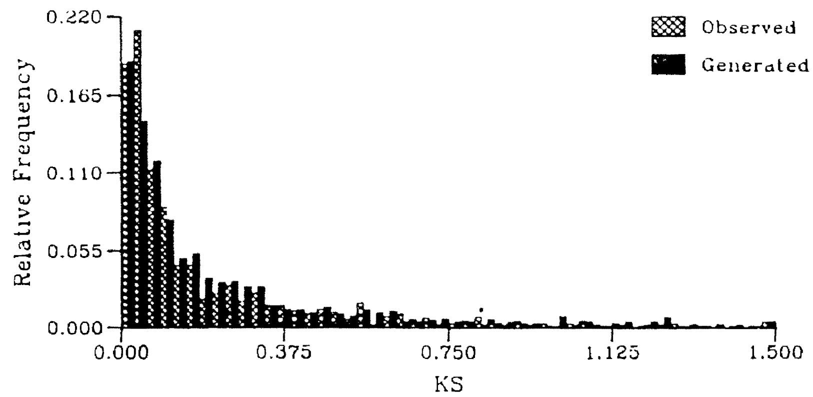


Fig. 9 Histogram of randomly generated saturated hydraulic conductivity K_s values and original observed data

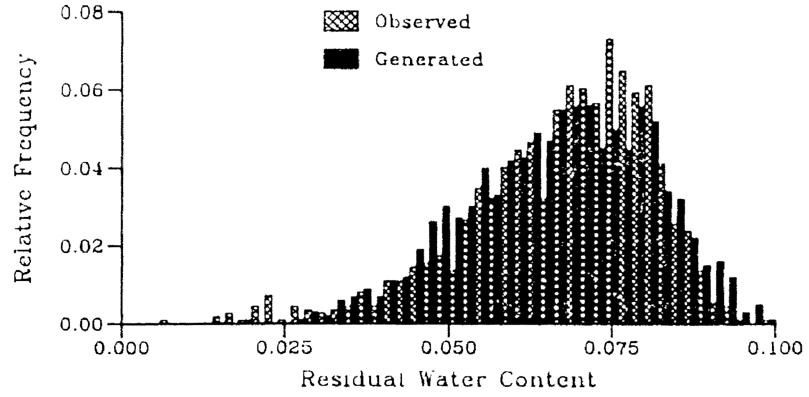


Fig. 10 Histogram of randomly generated residual water content Θ_r values and original observed data.

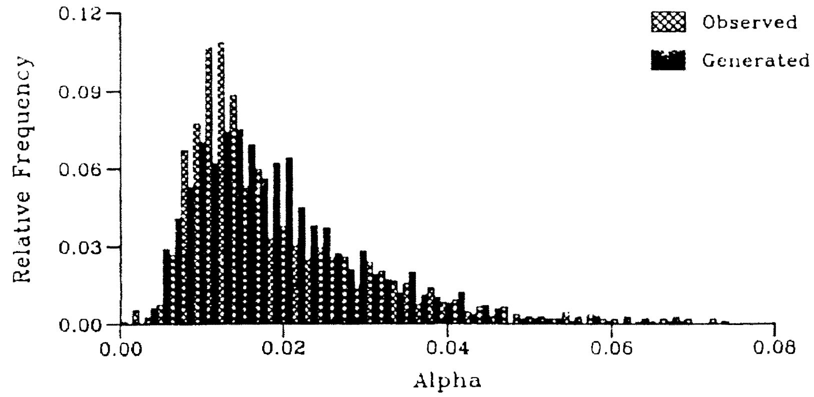


Fig. 11 Histogram of randomly generated *van Genuchten* [1976] water retention model parameter α values and original observed data

Figure 4. Comparison of soil properties generated by the computer program to actual field data (Carsel and Parrish, 1988).

Soil Air Permeability Calculations

Permeability is a measure of the connectivity of the soil's pore spaces and their ability to transmit fluids. It varies as a function of a soil's intrinsic permeability which is a measure of the relative ease with which a porous medium can transmit air or fluid, fluid saturation, liquid content. and air porosity (DiGiulio, 1992). Air permeability can be indirectly estimated using the randomly generated saturated hydraulic conductivity values and van Genuchten water retention parameters (α, N) obtained from the Carsel and Parrish program. The relationship between saturated hydraulic conductivity and intrinsic permeability is given by:

$$k_i = \frac{\eta_w k_s}{\rho_w g} \qquad (3)$$

where:

k_i = intrinsic permeability (cm/sec)
η_w = viscosity of water (0.01 g/cm /sec)
ρ_w = density of water (1 g/cm^3)
k_s = saturated hydraulic conductivity (cm/hr)
g = gravitational acceleration (980 cm/s^2)

Equation 3 will yield soil permeability at 100% fluid or air saturated conditions. In multiphase air/fluid systems, the individual phases interact causing reduced individual permeabilities. The permeability to any particular fluid becomes a function of the relative saturation of that fluid. For air permeability, the higher the air porosity the greater the permeability. The ratio of the effective or actual permeability at a given saturation to the intrinsic permeability is the relative permeability (DiGiulio, 1992). Relative permeability varies from one to zero and simply describes the variation in air permeability as a function of air saturation. Thus, air permeability (k_a) in unsaturated soils can be estimated by multiplying a soil's intrinsic permeability by the relative permeability (k_r) as shown by equation (4):

$$k_a = k_i k_r \tag{4}$$

In this study relative permeability was taken to be dependent only on the calculated air saturation and was held at a fixed value for each soil air permeability realization (Parker et al.; 1987). Air saturation was estimated as the difference between total porosity and water content (EPA, 1991).

For this project, total porosity was assumed to equal total water saturation. Total water saturation was estimated from a set of normally distributed values (generated by EXCEL random number function) that were then randomly assigned to each permeability realization. Mean values and standard deviation data used to calculate the normally distributed saturated water content values for each soil class were taken from the SCS data as reported by Carsel and Parrish (1988). Additionally, unsaturated zone soil moisture was taken at field capacity for all permeability calculations. Assumption of long-term steady state conditions were based on artificial ground cover is used during venting operations and typical field conditions. Ground cover which is used to prevent vacuum loss to the surface also acts to prevent infiltration in the venting area. Typically contaminated soils are at a sufficient depth to minimize daily moisture fluxes.

Field capacity was estimated using the van Genuchten (1980) model for predicting soil water content as a function of pressure head shown in equation 5:

$$\Theta = \Theta_r + \frac{(\Theta_s - \Theta_r)}{[1 + (\alpha h)^N]^M} \tag{5}$$

where:

Θ = water content at field capacity
Θ_r = residual water content
Θ_s = total saturated water content
α = empirical constant, cm-1
N = empirical constant
M = empirical constant
h = capillary head, cm

and where M is related to N as follows:

$$M = 1 - 1/N$$

Pressure head at field capacity was estimated at 355 cm (van Geunucthen, 1980). Field capacity varied for each permeability realization as a function of the random soil properties N, α, and Θ_r generated from the random generator program. A total of 2,880 (720 for each of four soil classes) permeability realizations were calculated from the randomly generated soil properties using equations 3-5. A sample spreadsheet of air permeability calculations is shown in Appendix B.

SOIL VENTING SIMULATIONS

Introduction

To analyze the effect of air permeability on venting efficiency, a series of soil venting simulations over a range of soil and operational conditions were performed. The simulations were constructed to reflect what might be typically encountered at actual UST or other cleanup sites. The flow chart shown in Figure 2 indicates the specific operational data and site conditions which were incrementally adjusted and modeled in this study, as well as the simulation framework followed for each soil class. A total of 12 different scenarios were simulated for each of 4 soil classes for a total of 48 simulations.

The model Venting2 (Environmental Systems & Technologies, Inc.; 1990) was used to simulate the venting process. This program was based on a series of analytical equations developed by Johnson et al. (1990a) and solves equations 1 and 2 by finite differences to compute the total recovery and individual component recoveries versus time. It also computed the phase distribution and soil concentration of the remaining hydrocarbon for the specified venting conditions. The model was tested against both field and lab data and found to adequately predict results for both weathered and fresh gasoline compositions (Johnson et al.; 1990a).

Each simulation was run using the range of expected air permeability values randomly generated for that soil class. Incremental time steps were established to evaluate model output on an annual basis. Model output was saved to a file for later use in developing probability plots. Representative model output is shown in Appendix C.

Chemical File - Development of Composite Gasoline

A gasoline contaminant spill was selected for evaluation in this study. Based on the number of UST's storing gasoline and pipelines used for transportation, it was considered the most common volatile organic contaminant leaked to the subsurface. "Gasoline" is actually a generic name for a complex mixture of as many as 180 hydrocarbon compounds consisting of alkanes, alkenes, naphthenes, and aromatics (Weaver, 1992). The majority of these compounds is present only in relatively dilute concentrations of less than one tenth of one percent and are assumed to present no health risk because they are readily biodegraded in many soils. With the exception of their cumulative mass in soil (measured as TPH), these components are not presently under any state or federal regulations. A few of the chemical compounds found in gasoline, however, do occur in large enough amounts to pose a health risk or are under regulatory control. It was these compounds which were also of interest in this study.

Because this study concentrated only on a fraction of the components that make up gasoline and because of the varied composition between brands of gasoline, a composite gasoline was created as the contaminant to be modeled by the Venting2 program. From a possible 180 components, nine were selected to represent an average unleaded gasoline. They were benzene, toluene, ethylbenzene, and [o- m- p-] xylene (BTEX), methyl tertiary butyl ether (MTBE), n-hexane, and naphthalene. Using these nine components to represent a gasoline's toxic potential is supported by monitoring data and the toxicity of other gasoline components (Hartley and Ohanian, 1989). It was also consistent with previous modeling efforts (Donaldson et al.; 1990; Johnson et al., 1990 and USEPA 1991).

Specific individual components and their concentrations used to represent composite gasolines vary depending on the study. For example, Johnson et al. (1990) used 58 components to model a typical regular gasoline spill while Donaldson et al. (1990) used only 10 for their synthetic gasoline. The common link between various composite gasolines examined was that components regulated as hazardous substances were always considered individually. Table 6 shows a comparison of concentrations used in this study and those most frequently reported in natural and composite gasolines. All the compounds listed in Table 6 are currently regulated except for MTBE. MTBE is an additive commonly found in gasoline where Its used mainly to boost octane. Although not frequently reported as a major part of gasoline, MTBE was included because it had the second highest concentration compared to the regulated compounds in Table 6.

Table 6. Comparison of the Major Component Concentrations Reported in Natural and Simulated Gasolines.

Compound	Concentration (mass %)						
	A[1]	B[2]	C[3]	D[4]	E[5]	F[6]	This Study
Benzene	0.81	1.94	3.00	0.76	2.00	2.11	1.80
Toluene	12.02	4.73	5.00	5.50	10.0	6.67	7.30
Ethylbenzene	1.70	2.00	2.00	-	-	1.94	1.90
M-Xylene	3.83	5.66	7.00	0.00	1.00	2.56	3.30
O-Xylene	1.93	2.27	-	0.00	1.00	2.56	2.10
P-Xylene	1.58	-	-	9.50	1.00	2.56	4.70
N-Hexane	-	1.08	9.00	2.83	2.00	-	3.70
Naphthalene	0.10	-	-	0.45	-	0.88	-
MTBE	-	-	-	-	10.0	3.5	5.30

References:

1. Natural gasoline; EPA, 1988a.
2. API PS-6 gasoline; Hartley and Ohanian, 1990.
3. Synthetic gasoline; EPA, 1991a.
4. "Typical " regular gasoline; Johnson et al., 1990.
5. "Typical" commercial gasoline (weighted average); Weaver, 1992.
6. Average of six unleaded gasolines; Potter, 1990.

Individual component concentrations ranged from less than one percent to eight percent. Component concentrations used in this study approximate an average of reported values. Individual chemical properties of the composite gasoline used in this study are shown in Table 7. To insure proper mass balance while monitoring overall venting performance, the minor compounds not included in the chemical file were represented by composite light and high end components (based on molecular weight) and mass weighted chemical properties were assigned (see Appendix D for calculations). The compounds listed in table 7 also reflect the order in which they will be recovered during soil venting.

Table 7. Selected physio-chemical properties (at 20°C) of the composite gasoline used in this study[1].

Representative Compound	Concentration (% w/w)	Mole Weight (g/mol)	Boiling Point (oC)	Vapor Press. (atm)	Solubility (mg/l)	Kow
Light-End	38.7	78.3	41.6	0.844	45	8806
MTBE[3]	5.30	88.1	55.2	0.328	51,000	17.4
N-Hexane	3.73	86.2	69	0.16	13	8,710
Benzene	1.77	78.11	80	0.10	1,780	135
Toluene	7.32	92.14	111	0.029	515	490
Ethylbenzene[2]	1.91	106.17	136.2	0.0092	152	1,410
P-Xylene	4.70	106.17	138	0.0086	198	1,413
M-Xylene	3.30	106.17	139	0.0080	162	1,585
O-Xylene	2.10	106.17	144	0.0066	175	589
Heavy-End	31.2	131.1	174.9	0.0026	32	60034

Sources:

1. Johnson, P. C., et al., 1990 except concentrations from Table 6.
2. USEPA, 1990a. Appendix A
3. Howard, P.H., 1993

They have been arranged in descending order according to their vapor pressure. Thus the light ends of this composite gasoline will be recovered first followed by MTBE and so forth. These composite components together with the nine regulated chemical compounds exhibited similar removal did their equivalents in a gasoline approximated by 58 compounds. In this way the regulated materials as well as the TPH behaved in a manner consistent with more complex mixtures when soil venting was simulated.

Regulatory Framework

A survey of regulatory requirements, based on data from 40 states, indicated that these state agencies used TPH as one means to measure the extent of soil contamination resulting from a spill or tank leak of petroleum products (Bell et al.; 1990). Thirty-four states also used TPH either as guidance level for cleanup or as a site-specific remediation goal. The majority of states required 1000 ppm or less with as few as low as 100 ppm. Additional analytical measurements of BTEX, MTBE, or polynuclear aromatic hydrocarbons may also be required. To be consistent with this regulatory framework, this effort selected intervals as well as total time periods appropriate to define contaminant capture potentials. That is, sufficiently small time steps were chosen to allow a complete recovery curve to be generated for each of the components listed in Table 6. Similarly, a sufficiently long period of time was selected for total simulation length to approximate field conditions not limited by process economics. Total simulation periods were set at five years to be consistent with field efforts where greater time frames could be employed when potential risk to human health was sufficiently low enough to warrant longer term remediations. However, it is generally held that if total recovery times are greater than two years then soil venting is not a feasible process selection (USEPA 1991b). Based on these regulatory considerations, all venting simulations were run for five years or until TPH was less than 500 ppm and individual components were completely recovered.

RESULTS AND DISCUSSION

Monte Carlo Analysis Results

Sample Size

A total of 720 permeability realizations were made for each of four soil classes. Running sample means of air permeability and standard deviation were calculated for every 10 realizations and plotted for increasingly larger populations. Representative data plots for two of the four soil classes evaluated are shown in Figures 5-6. These plots served as a check on the completeness of the sample populations. Convergence of the data to near constant values was accomplished after approximately 250-300 realizations with only slight variations thereafter. Constant values indicate that the populations were statistically complete and the data sets sufficiently large enough to ensure accuracy.

Descriptive statistical summaries of calculated air permeabilities are shown in Table 8. Soil types were arranged in descending order according to the magnitude of their mean

Table 8. Descriptive statistics for calculated soil air permeabilites (darcy).

Soil Class	Mean	Median	S.D.	CV (%)	Min/Max
Sand	3.23	2.88	1.73	53.5	0.31/9.25
Loamy Sand	1.48	1.03	1.34	90.5	0.009/7.00
Sandy Loam	0.41	0.23	0.49	119.5	0.009/3.72
Loam	0.09	0.03	0.15	166.7	0.0003/1.23

S.D. = standard deviation and CV = coefficient of variation.

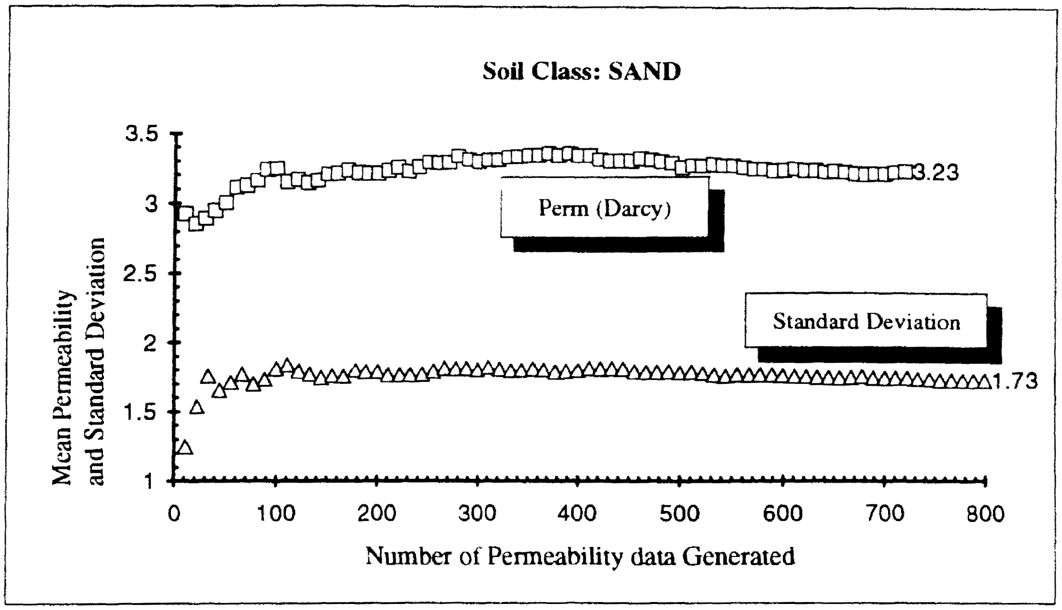


Figure 5. Sample size analysis for sand soil.

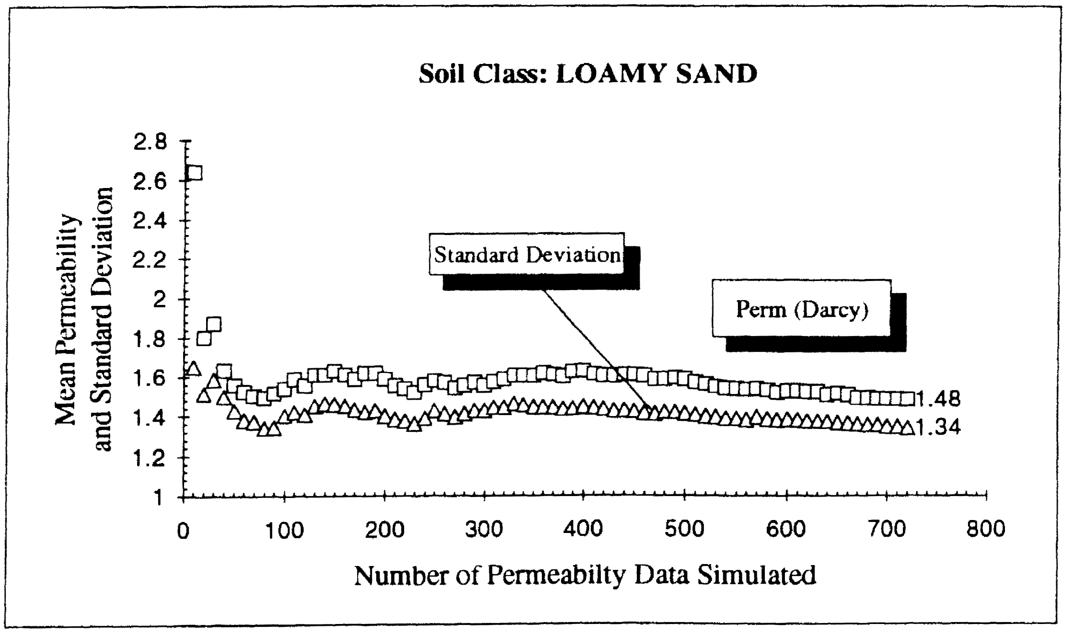


Figure 6. Sample size analysis for loamy sand soil.

air permeability. Examination of Table 8 indicated a correlation between permeability and the CV. As permeability decreased, the CV increased. A threefold increase in CV could be seen, ranging from 53.5% in sand to 166.7% in loam. This relationship was attributed mainly to the interaction of increasing clay and decreasing sand content of the soils. As a soil's sand content decreases, causing available pore space to decrease, the soil becomes more sensitive to the effects of increasing clay content (in terms of air permeability). Referring back to Table 3, average clay and sand content for sand was 2.9% and 92.7% respectively versus 19.7% and 40.0% for loam. The result of the increased CV was a range of air permeability that spans four orders of magnitude for loam soil versus only one order of magnitude for sand soil. Based on the CV, it can also be inferred that a higher degree of uncertainty was more likely when estimating air permeability for loam and sandy loam soils than for sand and loamy sand soils.

Determination Of Probability

Analysis of the air permeability required that the data be first ranked in descending order by soil class. Plotting positions within each soil type were then determined using the Weibull plotting position formula which is simply: ordered rank position divided by sample size plus one (Chow, 1964). The underlying probability distributions of air permeability within each soil class were then determined from normal probability plots of the data. Plots of air permeability data were constructed using the SYSTAT statistical plotting software (SYSTAT, Inc., Evanston, Illinois, 1993). Each plot was made using all

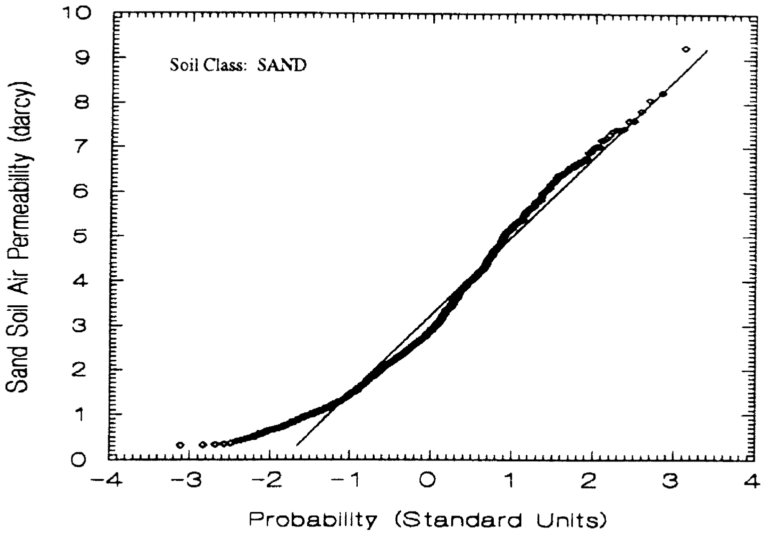
720 air permeability realizations generated for each soil class. Figures 7-8 present the results of the plots for each soil class. Probabilities were shown as standardized normal distribution units (also referred to as Z-scores). These values could be expressed as percent probabilities as shown in Table 9. Use of Z-scores allowed normal probability plots to be shown on arithmetic scales. Z-scores of one and minus one also corresponded to one standard deviation above and below the mean which had a Z-score of zero.

Table 9. Standardized normal values as percent probability.

Z	P(z) as %	Z	P(z) as %
-3.0	0.13	0.5	69.15
-2.5	0.62	1.0	84.13
-2.0	2.27	1.5	93.32
-1.5	6.68	2.0	97.72
-1.0	15.87	2.5	99.38
-0.5	30.85	3.0	99.87
0	50.0		

Source: Haan, (1977)

Based on the best linear approximation obtained with SYSTAT, soil air permeabilities for all soil classes were found to approximate a normal distribution over the majority of the data. Loamy sand, sandy loam, and loam soil permeabilities approximated a normal distribution after the data was smoothed by log transformation. Slight variances at the upper and lower tails of the sample distributions were noted in all soil classes, however. Data in the range below 2.5 standard deviations (Z-score of 2.5) represented extreme events with less than one percent probability of occurrence. Although



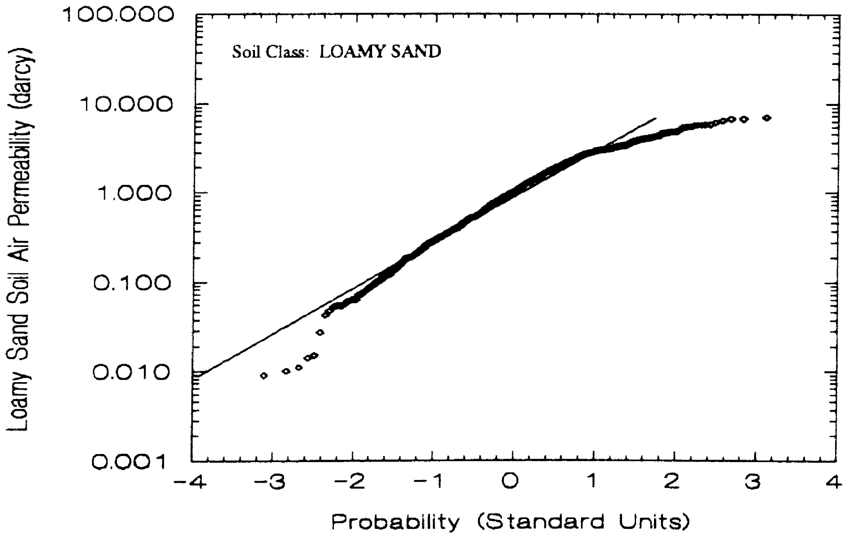
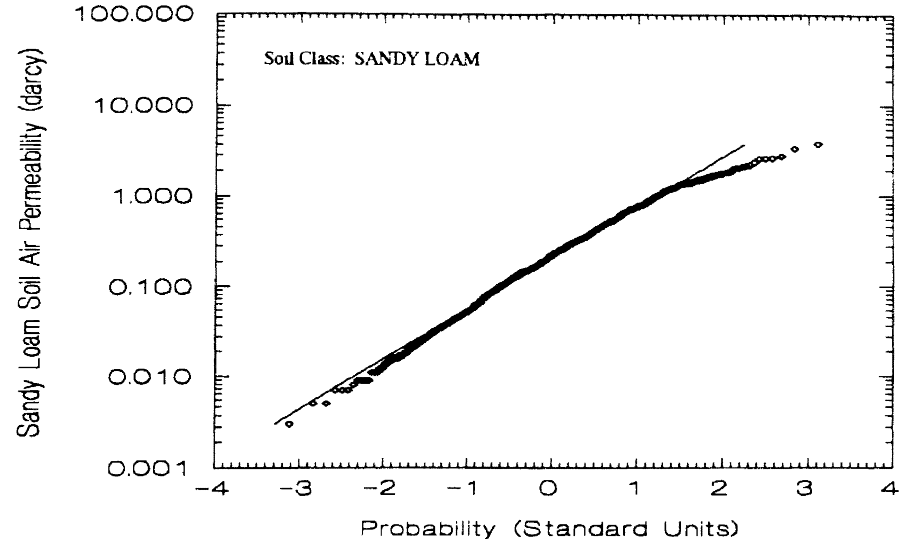


Figure 7. Normal probability plots for sand and loamy sand soils showing normal and lognormal distributions of air permeability. Sample size is 720 data points per soil.



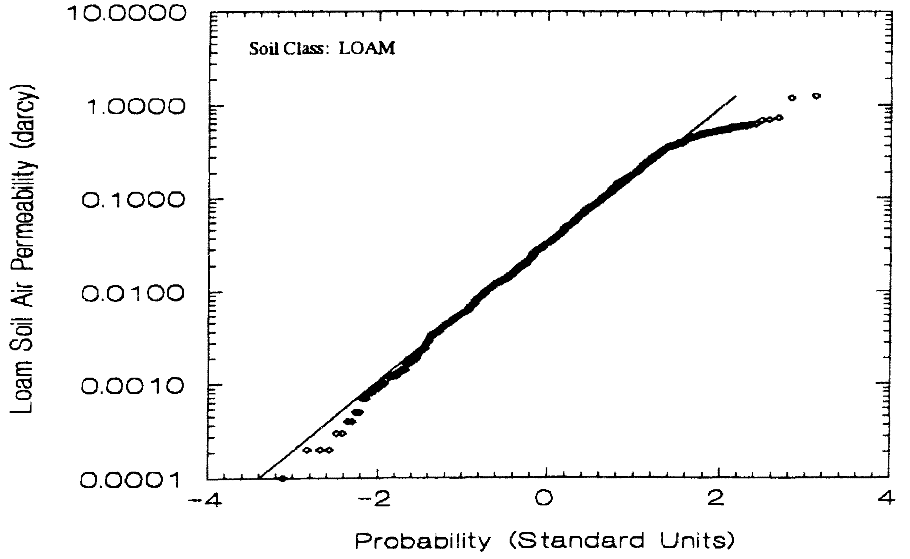


Figure 8. Normal probability plots for sand loam and loam soils showing lognormal distribution of calculated air permeability. Sample size is 720 data points.

statistically valid, the occurrence of these extreme values was not the major concern in this study because the focus here was on analysis of the more likely events. Therefore these deviations were not seen not to detract from the conclusion of overall normally distributed data. The significance of having normally distributed data was that it could be assumed that the correlation structure of the randomly generated soil parameters used to calculate air permeability was preserved and that the entire range of possible values was represented from a limited number of observations. Additionally, individual probabilities may then be assumed to represent points of a continuous function which could be plotted and shown with a best fit line.

After the distribution of air permeability data was determined for each soil class, the magnitude of expected air permeability over a range of probabilities from 1 percent to 99 percent was selected from the theoretical best fit line from each plot. These values are presented in Table 10. The smallest range of permeability values occurred in the sand soil, which varied by only one order of magnitude. The largest variation occurred in the loam soil, which varied by three orders of magnitude at the probability levels selected. Again, the wide range in loam soil air permeability was related to decreased sand and increased clay content as previously discussed. From Table 10 its apparent that some permeability values were present in all soil classes. However, the likelihood of these same permeability values occurring varied widely. For example, in a sand soil a 2.50 darcy permeability had 60% probability of occurrence while in a sandy loam soil the same approximate value only had a 1% probability of occurrence.

Table 10. Magnitude and probability of air permeability (darcy) by soil class.

Probability of (x) Equal Or Greater Than (%)	Sand	Loamy Sand	Sandy Loam	Loam
1	7.42	5.80	2.32	0.610
10	5.78	3.34	1.08	0.300
20	4.82	2.66	0.655	0.140
30	4.07	1.93	0.430	0.081
40	3.44	1.40	0.306	0.050
50	2.88	1.03	0.225	0.033
60	2.50	0.77	0.156	0.021
70	2.12	0.52	0.114	0.013
80	1.64	0.34	0.068	0.008
90	1.15	0.19	0.036	0.004
99	0.43	0.042	0.008	0.0004

This result was indicative of the problem with selecting air permeability values from tables. Although the permeability value were well within the range of values (see Table 6) for each soil, the estimate for the sandy loam soil was likely to be significantly over-estimated based upon its 1% probability of occurrence.

Overall, the general magnitude of the generated air permeability data for each soil class agreed with mean hydraulic conductivity data published by van Genuchten et al. (1991), indicating that these data were consistent with other efforts. Therefore, if an air permeability value is required for other unsaturated zone modeling, Table 10 could be used to estimate that value with more confidence over those which simply state a range.

Development Of Soil Venting Probabilities

According to the EPA (1991a), soil venting should be considered a potential remedy if mathematical modeling predicts that cleanup can be achieved in two years or less. Thus the initial analysis effort focused on evaluating the probability of reaching cleanup target levels after two years of soil venting. Depending on the two year results, simulations were also evaluated at time increments other than two years in order to more accurately define cleanup time. For example, if the two year venting probability plot indicated a high probability of achieving a TPH concentration much less than 1000 mg\kg, the same scenario was evaluated at a one year increment. Thus the probability of achieving a particular cleanup goal within a specified time could be more narrowly defined.

Probability referenced air permeabilites were sequentially input into the VENTING2 model to evaluate percent hydrocarbon recovery, total petroleum hydrocarbon (TPH), and BETX soil concentrations for a variety of spill and operational conditions. The simulations were conducted according to the research structure shown in Figure 2. Each venting scenario was evaluated over the range of expected air permeabilites for each soil class as shown in Table 10. Simulation output for each soil class is summarized in Appendices E,F,G,and H. Each summary lists percent hydrocarbon recovery, as well as initial and final soil concentrations of TPH, BETX plus Napathene and MTBE, and Benzene (alone) for two different venting time periods for each simulation run.

As previously discussed, the resultant outputs (i.e. percent recovery and soil concentrations) for each model run were assigned the same probability as the air permeability that was input into the model. For example, if a sand soil air permeability was input with a 40 percent probability of occurrence, the predicted TPH soil concentration and percent hydrocarbon removed would have a 40 percent chance of occurring given the conditions simulated. Thus, probability-based nomographs were developed by plotting percent probability versus percent hydrocarbon removal and TPH soil concentration for each simulation. A line was then fitted through the plotted data because the results of each simulation represented points of a continuous probability function.

To enhance the utility of the nomographs, a distance weighted least squares (DWLS) curve rather than a straight line was fitted to the plotted points using SYSTAT. The DWLS curve was produced from a weighted quadratic multiple regression on all the data points. Although the line obtained in this manner might not represent an exact theoretical distribution (Chow, 1964), neither does the data which were only approximately normal. Curve fitting was warranted because its method of calculation honored the actual data better than forcing a straight line. Thus, when evaluating probabilities from these plots, results which more accurately reflect the data may be obtained.

Soil Textural Class Venting Probabilities

One of the goals of this study was to predict soil venting success based on knowledge of spill size and soil type only. This was accomplished by plotting probability of expected TPH soil concentration as a function of spill size for each soil class (Figures 9-12). Each point on these plots represented a separate soil venting simulation with varying operational parameters of two year duration. Thus these plots showed the probability of achieving TPH soil concentrations at the end of two years for a 1,000; 5,000; and 10,000 gallon composite gasoline spill. These probabilities were inclusive for all combinations of operational parameters considered and did not distinguish between individual parameters. For example, a point on a 5,000 gallon line which indicated 70 percent probability of 1000 mg/kg could be read as a combination of screen length, extraction vacuum, and contaminated soil volume for which venting may reduce TPH to that level in two years. The purpose of these plots was to serve as an initial screening tool to generally indicate whether soil venting was feasible (for a two year remediation). If venting appeared feasible, additional plots (see next section) would be consulted to determine which combinations of operational parameters indicated the highest probability of success.

If an estimate of spill size was not available, field estimates of initial TPH concentration data could also be used to predict venting success. For the three spill sizes considered here, initial soil concentrations of TPH (as calculated by the venting program) varied slightly from soil to soil due mainly to differing bulk density, water content, and porosity values. Recalling that two contaminated zone thickness (screen lengths) were

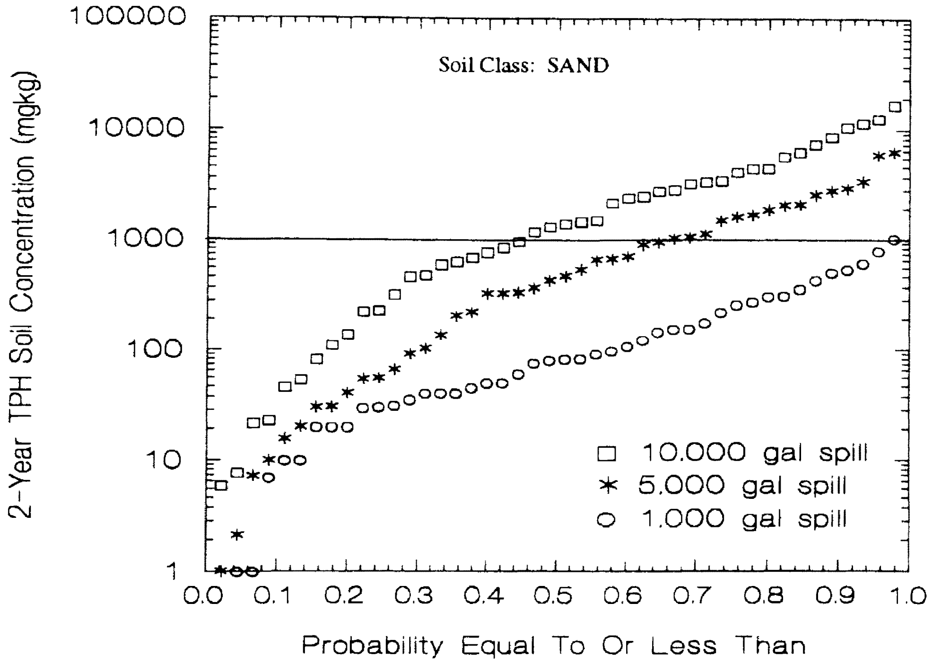


Figure 9. Probability of expected TPH soil concentration after a two year venting period. Plot shows results of all sand soil simulations.

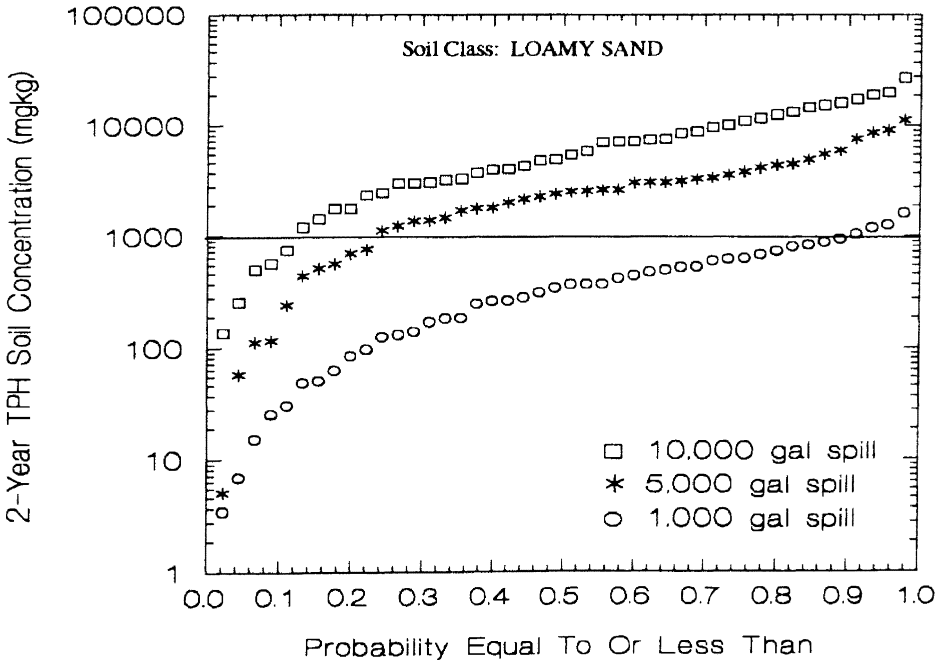


Figure 10. Probability of expected TPH soil concentration after a two year venting period. Plot shows results of all loamy sand soil simulations.

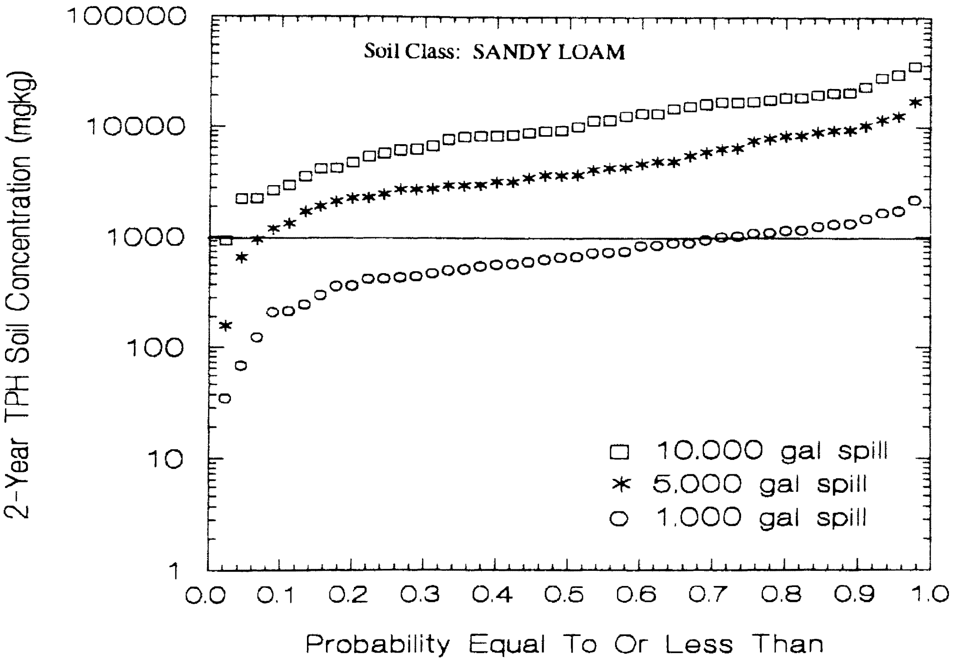


Figure 11. Probability of expected TPH soil concentration after a two year venting period. Plot shows results of all sandy loam soil simulations.

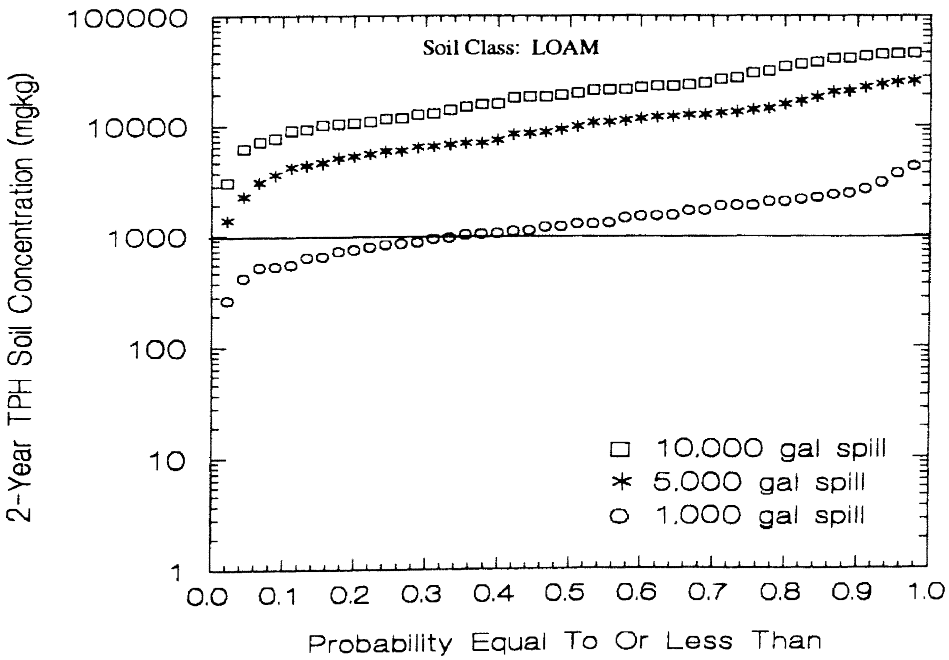


Figure 12. Probability of expected TPH soil concentration after a two year venting period. Plot shows results of all loam soil simulations.

simulated, average initial TPH soil concentrations for the 1,000 gallon spill size simulations were 2,000 and 4,000 mg/kg. For the 5,000 gallon spill simulations, average initial TPH soil concentrations were 10,000 and 20,000 mg/kg. For the 10,000 gallon spill simulations, average initial TPH concentrations were 20,000 and 40,000 mg/kg. To estimate the probability of venting success in this way simply substitute an initial TPH concentration range for the appropriate spill size. For example, suppose field data indicated a soil concentration of 7,500 mg/kg TPH in a loamy sand soil. Since 7,500 m/kg is between the range of 5,000 and 10,000 mg/kg, the 5,000 gallon spill size curve is selected on the loamy sand soil plot (Figure 10) and probability is read at the desired TPH concentration level.

A line through the 1,000 mg/kg TPH concentration level was drawn as an illustrative remediation goal to show relative efficiencies of soil venting at the various spill sizes. Analysis of these plots indicated that soil venting success for all spill sizes was predicted to be highest in the sand soil (Figure 9) and lowest in loam soil (Figure 12). Because the slope over the majority of the individual spill curves remained fairly constant, relative probability of venting success did not appear to be sensitive to spill size. This suggested that the process of soil venting does not favor a particular spill size over another except in venting time required to reduce TPH. An increase of slope in the 10-20 percent probability range indicated that certain combinations of operational parameters in conjunction with higher permeabilities could have a dramatic effect on venting success and that total venting time for the associated spill size may be much less than two years especially in the sand and loamy sand soils.

Based on the results of these plots, soil venting was generally not recommended for spills in the 10,000 gallon size range except in sand soils. The highest probability of success was 44 percent in the sand soil (Figure 9). The next highest probability was only 12 percent in the loamy sand soil (Figure 10). In sandy loam and loam soils there was virtually no chance to meet a 1000 mg/kg TPH cleanup goal and alternatives would be needed. For medium size spills in the 5,000 gallon range, soil venting should be pursued in the sand and loamy sand soils. In the sandy loam soil, there were only three cases (<10 percent of the simulations) where soil venting reduced TPH below 1,000 mg/kg. This indicated that, while possible, it was not probable that a spill of that magnitude would be cleaned-up in two years and alternatives or enhancements to the venting process should be investigated. Soil venting remediation of small spills in the 1,000 gallon size could be recommended for all soils. Probabilities of reducing TPH to 1,000 mg/kg ranged from 99 percent in sand to almost 50 percent in loam soil.

Figures 13-15 evaluate the effect of longer venting times on probability of success in loams and sandy loam soils. Generally, longer venting times of up to 5 years did not appreciably increase the probability of success for larger than 1,000 gallon spills. For example the 2 year probability of success associated with a 10,000 gallon spill in a sandy loam was approximately 4 percent. For a 5 year venting period it only increased to approximately 15 percent. This indicates that at certain low permeability levels there is very little that can be done to enhance system performance and that resources should be applied in other areas. For a loam soil at the 10,000 gallon spill size, even after 5-years of venting only one simulation was expected to go below the 1,000 mg/kg TPH level

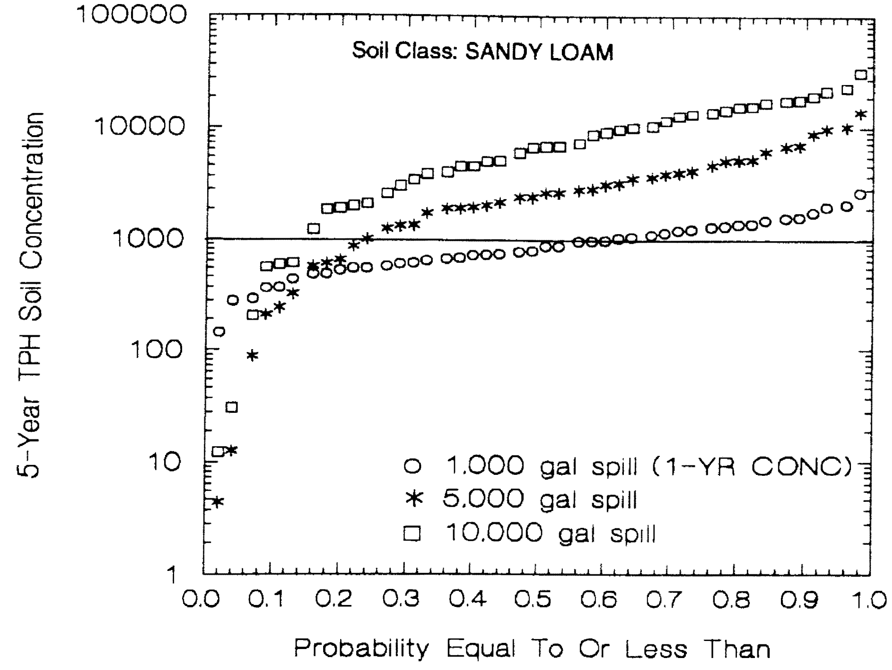


Figure 13. Probability of expected TPH soil concentration after a 5-year venting period. Plot shows results of all sandy loam soil simulations.

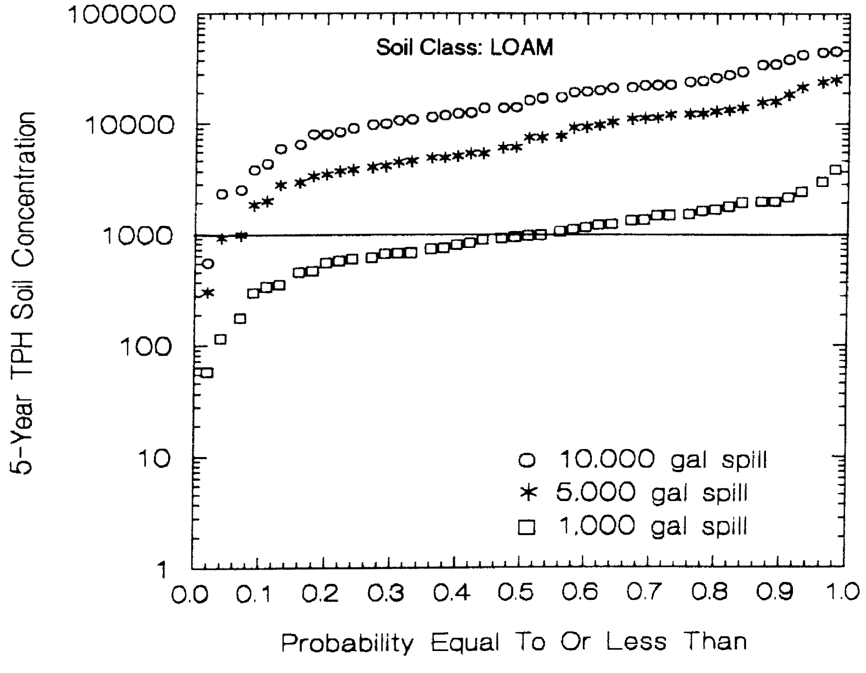


Figure 14. Probability of expected TPH soil concentration after a 5-year venting period. Plot shows results of all loam soil simulations.

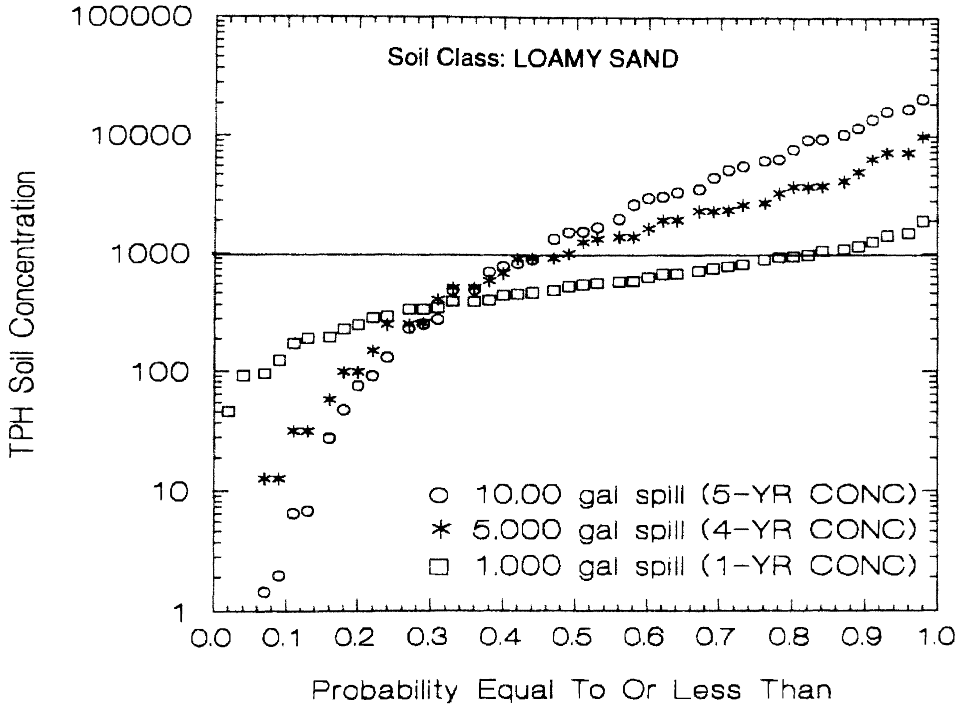


Figure 15. Probability of expected TPH soil concentration after a 5-year and other timeframe venting periods. Plot shows results of all loamy sand soil simulations.

further indicating the unsuitability of loam soils to soil venting for anything but the smallest of spills (1,000 gallons or less).

Individual Constituent Probabilities

An alternative to defining venting success with TPH concentrations is to use individual or select groupings of gasoline constituents. Increasingly, state regulatory agencies are now requiring or planning to require that two cleanup standards be met: one for TPH and another for selected individual components which are usually BETX (Bell et al.; 1990). The composite gasoline that was used in this study was created to allow easy tracking of these constituents. Referring to Table 7, the individual components followed in the venting model runs include BETX as well as two other components, MTBE and N-Hexane. For this discussion the components listed in Table 7 will simply be referred to as BETX. Although it varies by state, the regulatory limit of the sum of the concentration of BETX constituents in soils is much lower than for TPH. However, BETX as a group is easier to recover because it is much more volatile than TPH (see Table 7 for comparison). The EPA is also much more concerned with reducing BETX levels before TPH levels because BETX is more hazardous to human health (USEPA, 1991). Thus if soil venting cleanup goals can be based on BETX, wider applications with higher probabilities of success are possible.

The probability plots of the sum of BETX concentration at the end of a two-year venting period are shown in Figures 16-19. The value of these plots is best seen by comparing TPH and BETX venting probabilities in a soil that has low probability of

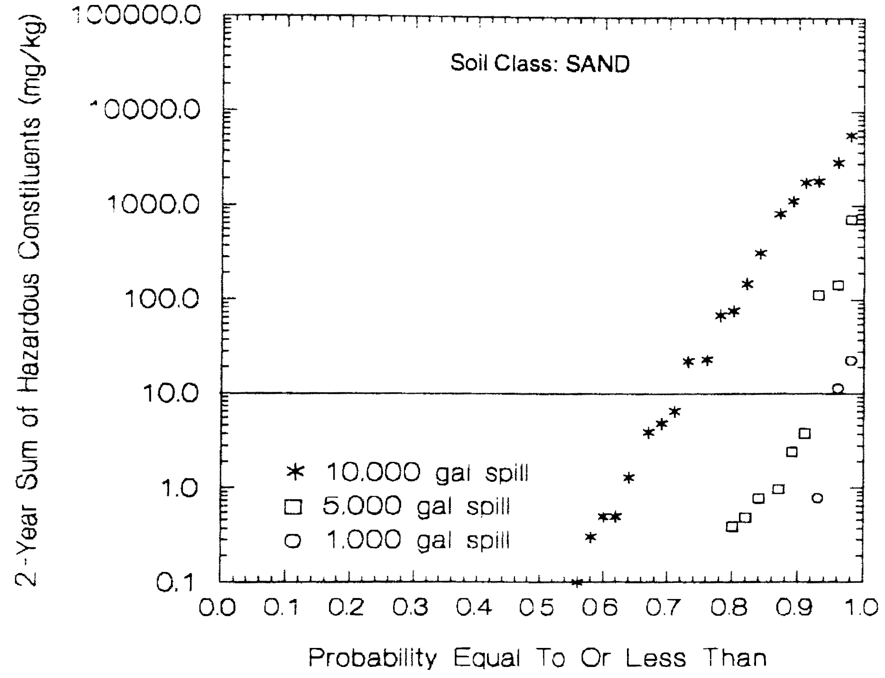


Figure 16. Probability of expected total BETX, MTBE, and N-Hexane soil concentration after a two year venting period. Plot shows results of all sand soil simulations.

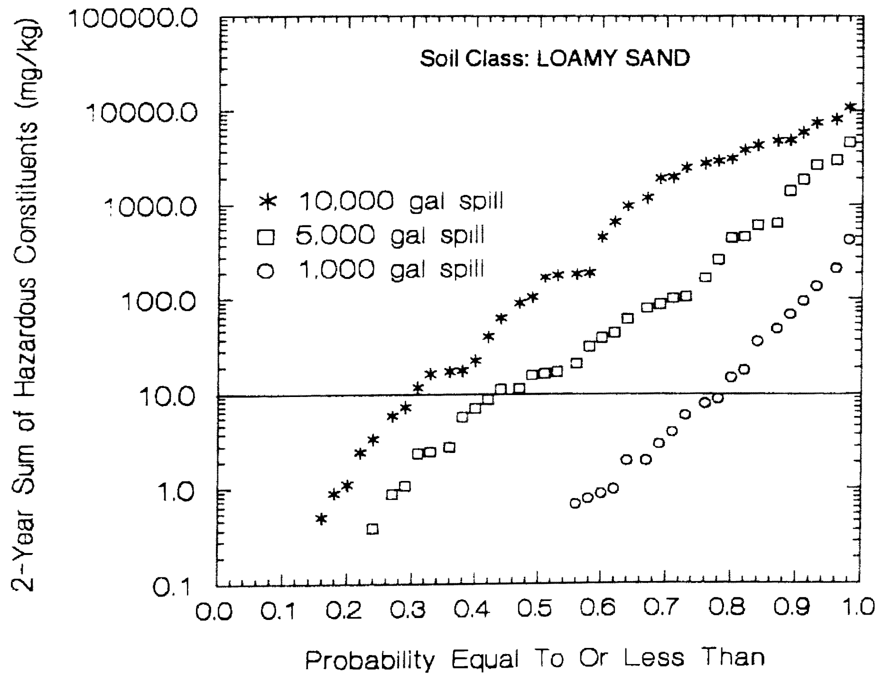


Figure 17. Probability of expected total BETX, MTBE, and N-Hexane soil concentration after a two year venting period. Plot shows results of all loamy sand soil simulations.

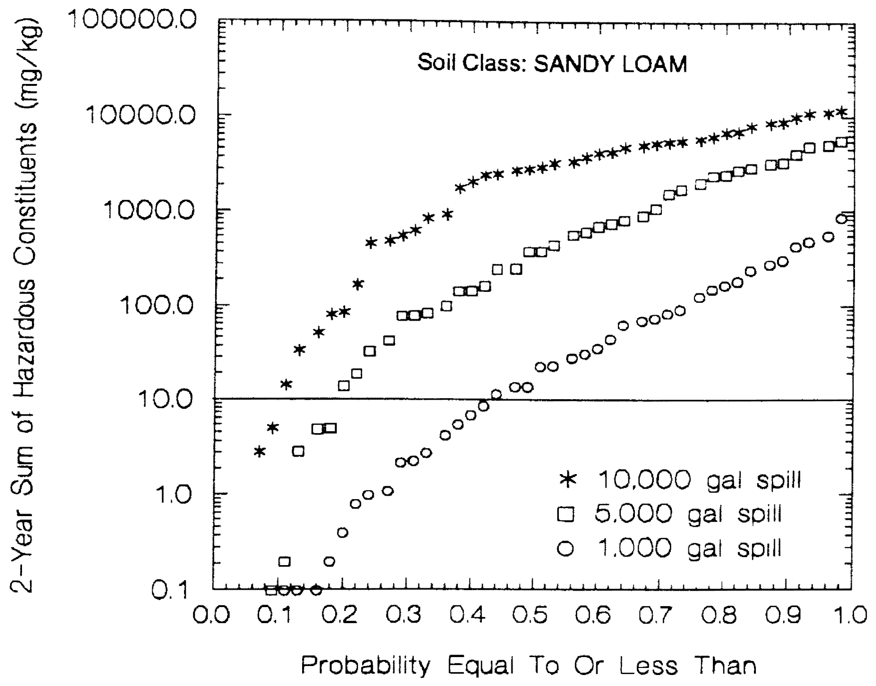


Figure 18. Probability of expected total BETX, MTBE, and N-Hexane soil concentration after a two year venting period. Plot shows results of all sandy loam soil simulations.

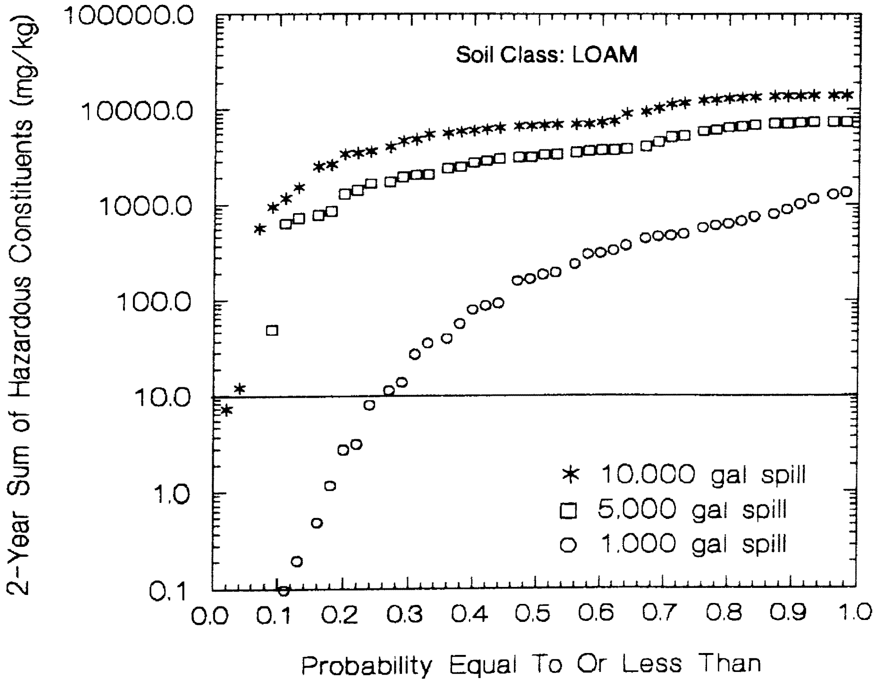


Figure 19. Probability of expected total BETX, MTBE, and N-Hexane soil concentration after a two year venting period. Plot shows results of all loam soil simulations.

success based on expected TPH concentrations. Comparing the probability of reaching 100 mg/kg TPH in a loam for a 1,000 gallon spill (Figure 12) which is much less than one to the probability of reaching 10 mg/kg BETX (Figure 19) which is 30 percent. Venting decisions based on BETX concentrations offer an alternative to not venting in a particular soil. Based on the higher probability of success in the example, venting could become part of a multi-pronged approach to site remediation.

Separate Probabilities

Prediction of the impact of operational parameters on the probability of venting success was provided by probability assessments for each combination of operational parameters. Figures 20-27 presents the results for a sand soil (plots for the other soil classes can be found in the appendix). These plots may be used to evaluate which combination of operational parameters offers the highest probability of venting success. They might also be used to determine trade-offs between system design options (i.e. screen length and extraction vacuum) which may impact operations costs with the probability of meeting cleanup goals. Probability of venting success was expressed in terms of an expected percent hydrocarbon recovery over the range of operational parameters for this series of plots. In this manner extra dimensions of accuracy and flexibility over the initial screening plots (Figures 9-12) are added. The reason lies in the fact that, when evaluating venting success with an initial TPH concentration from Figures 9-12, the range of TPH represented by the three spill sizes was wide enough at the larger

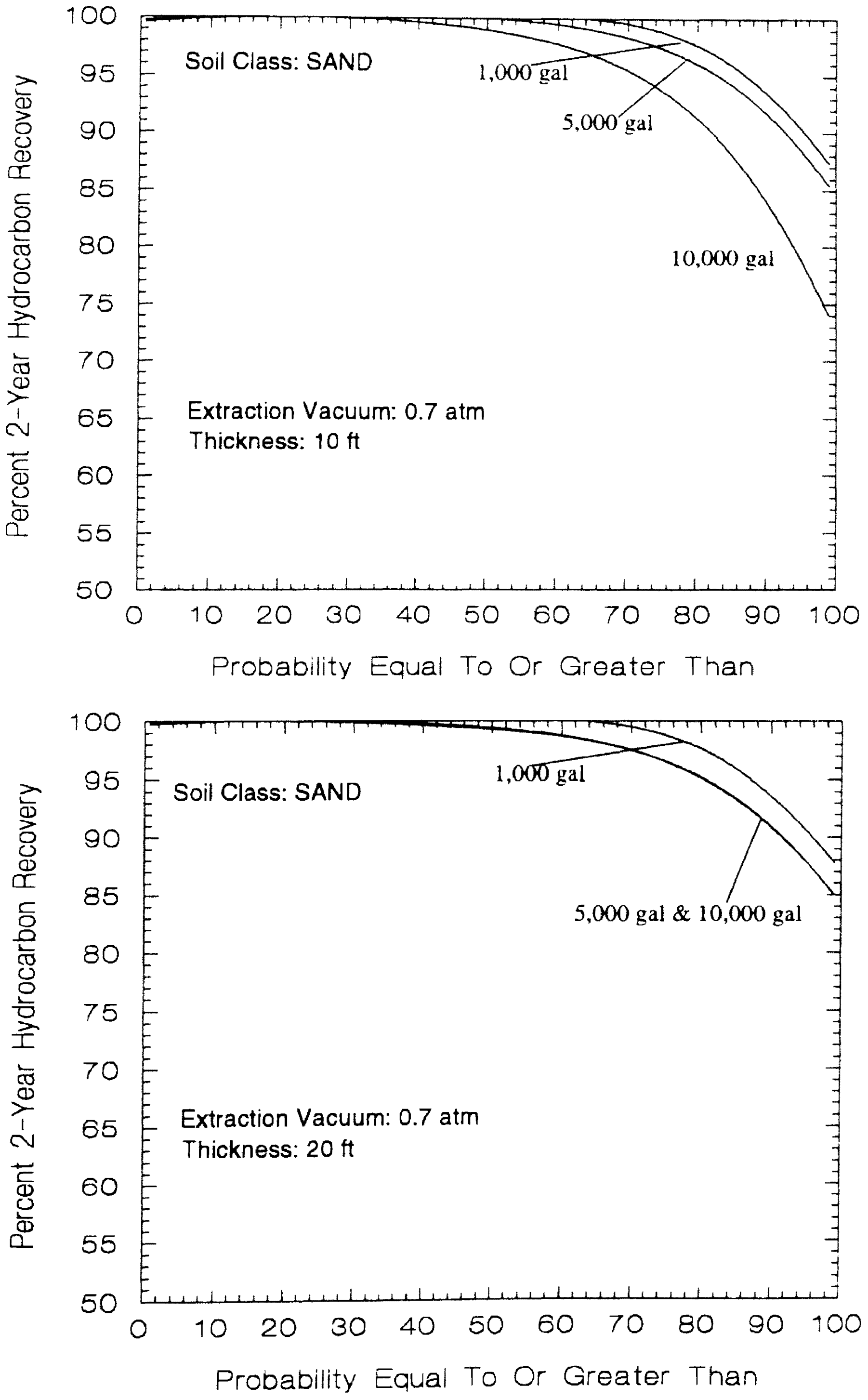
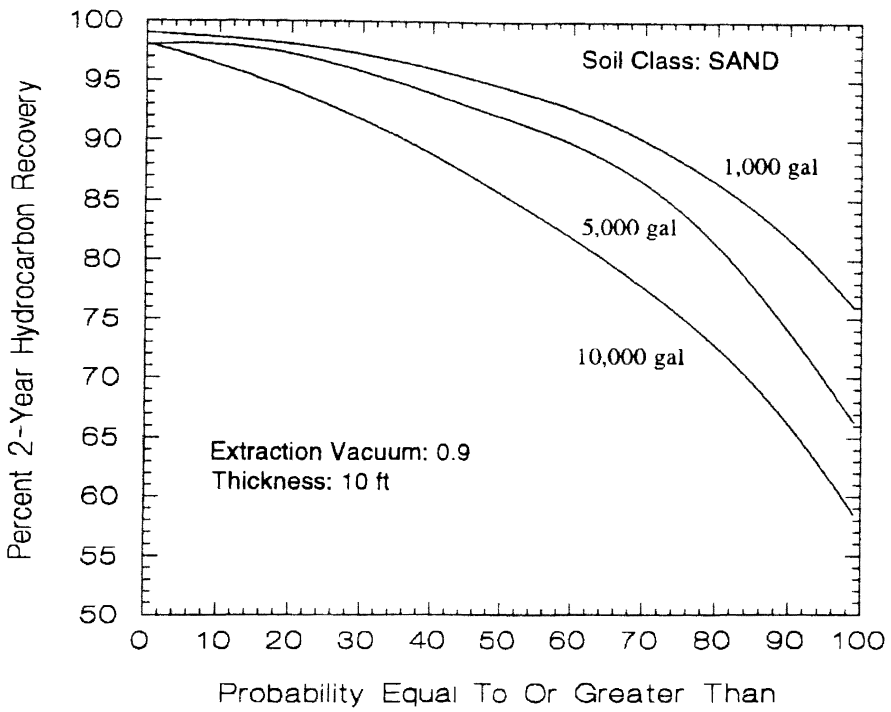


Figure 20. SAND SOIL control variable analysis plots for spill size showing the effecton 2-year hydrocarbon recovery using 0.7 atm vacuum and two thickness.



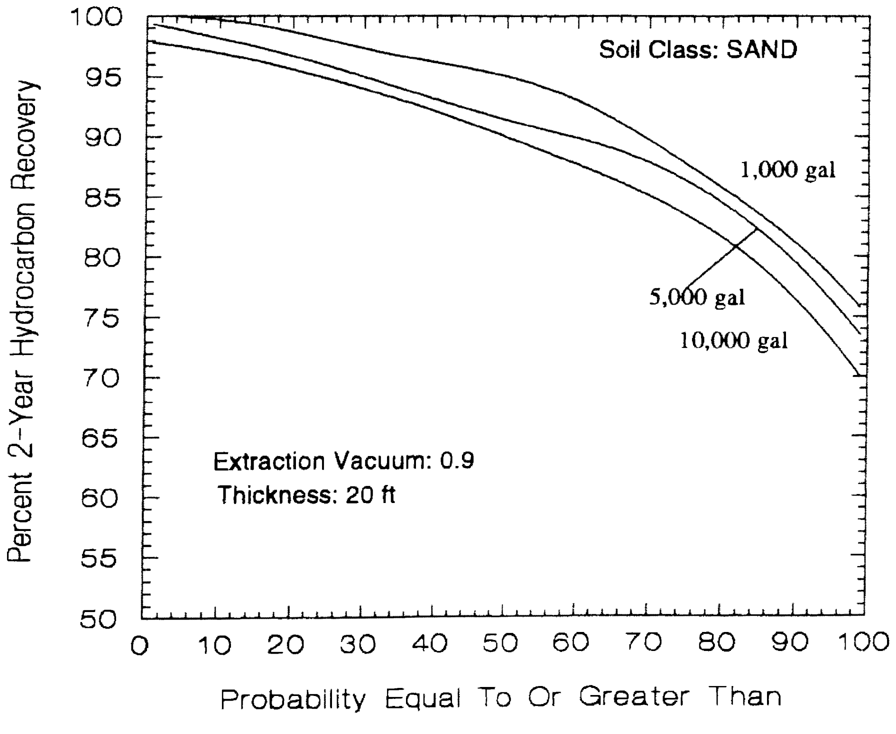
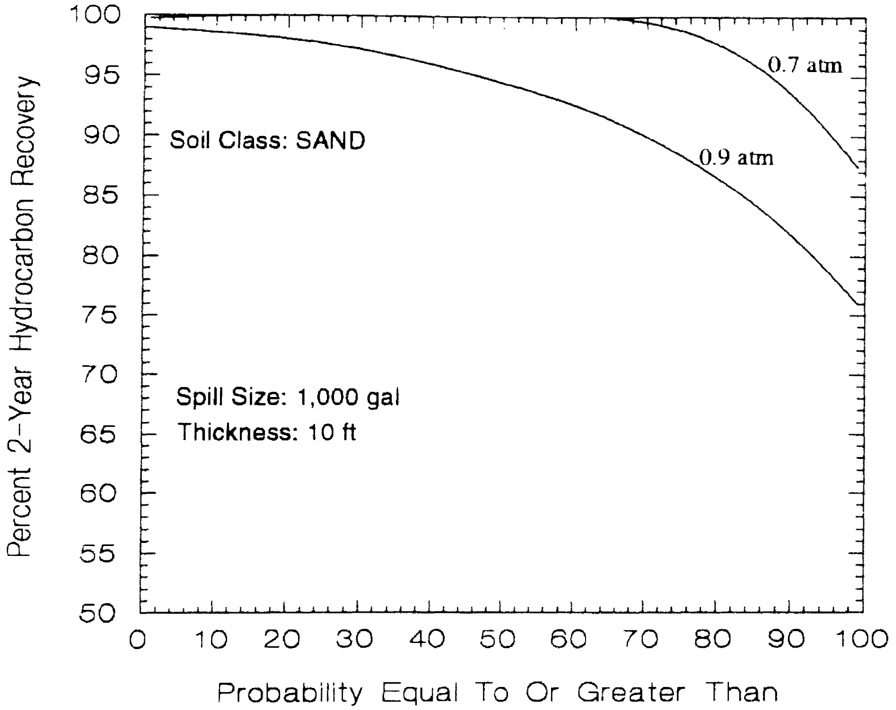


Figure 21. SAND SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.9 atm vacuum and two thickness.



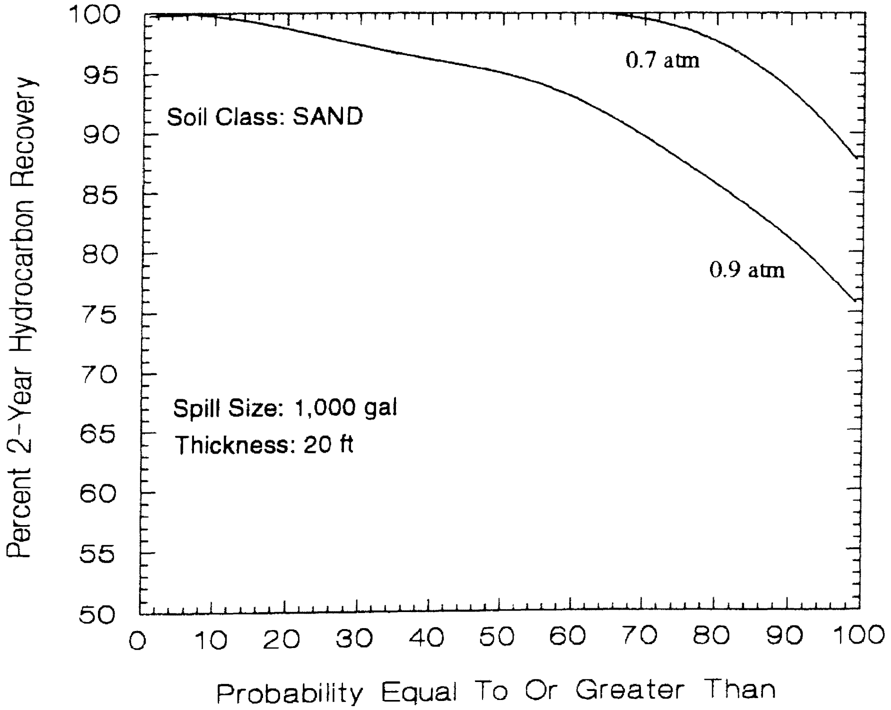


Figure 22. SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 1,000 gal composite gasoline spill.

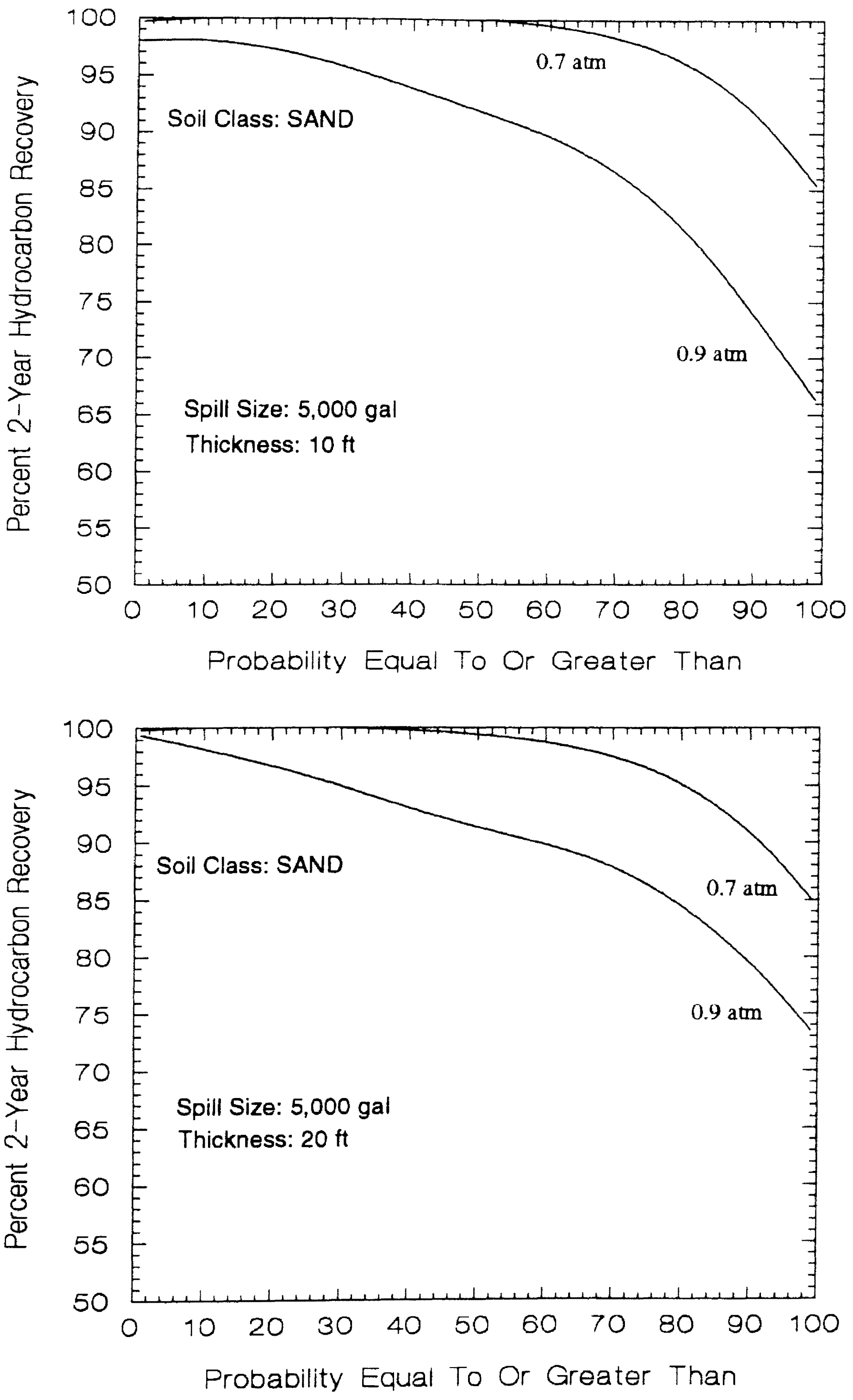


Figure 23. SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 5,000 gal composite gasoline spill.

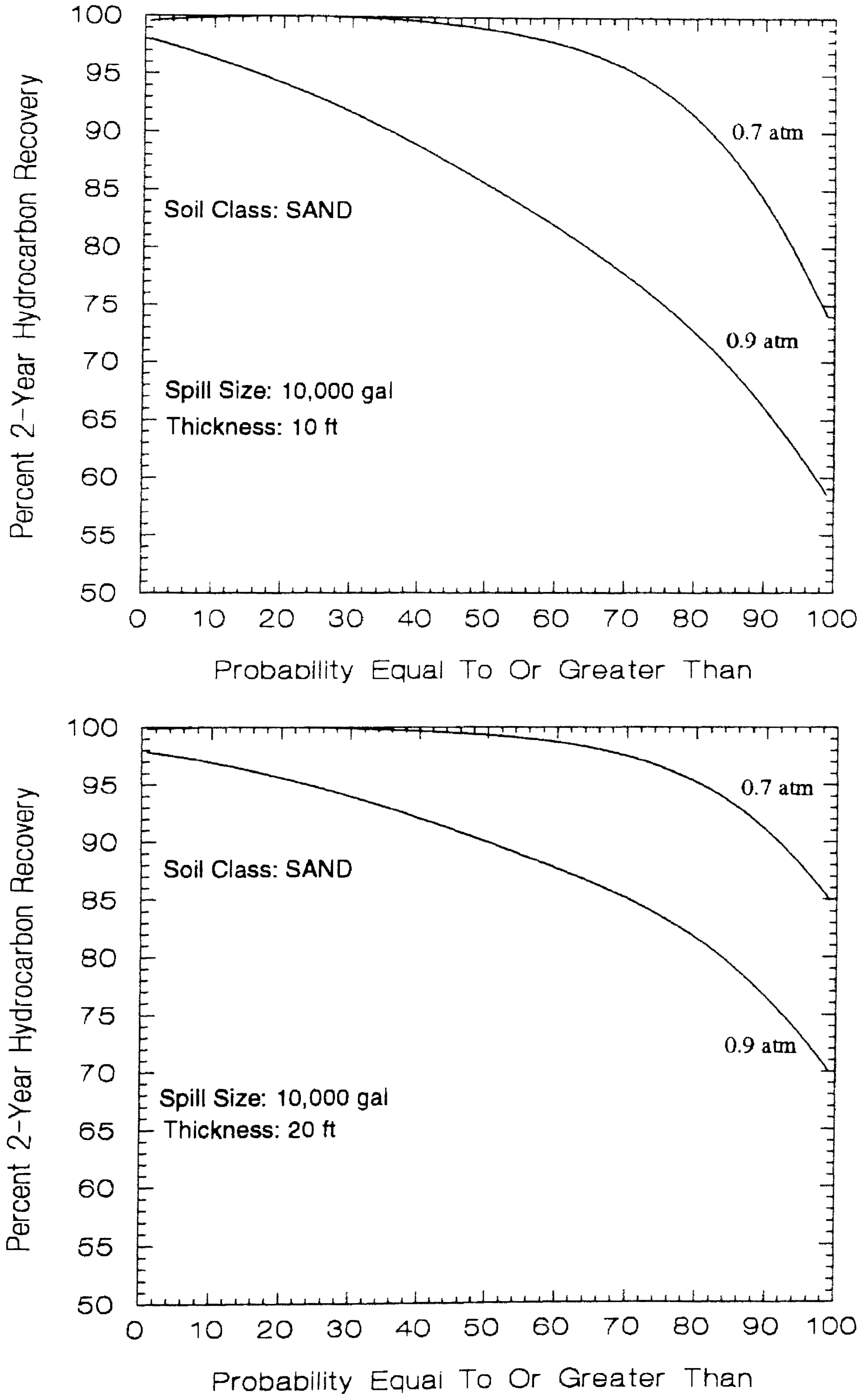


Figure 24. SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 10,000 gal composite gasoline spill.

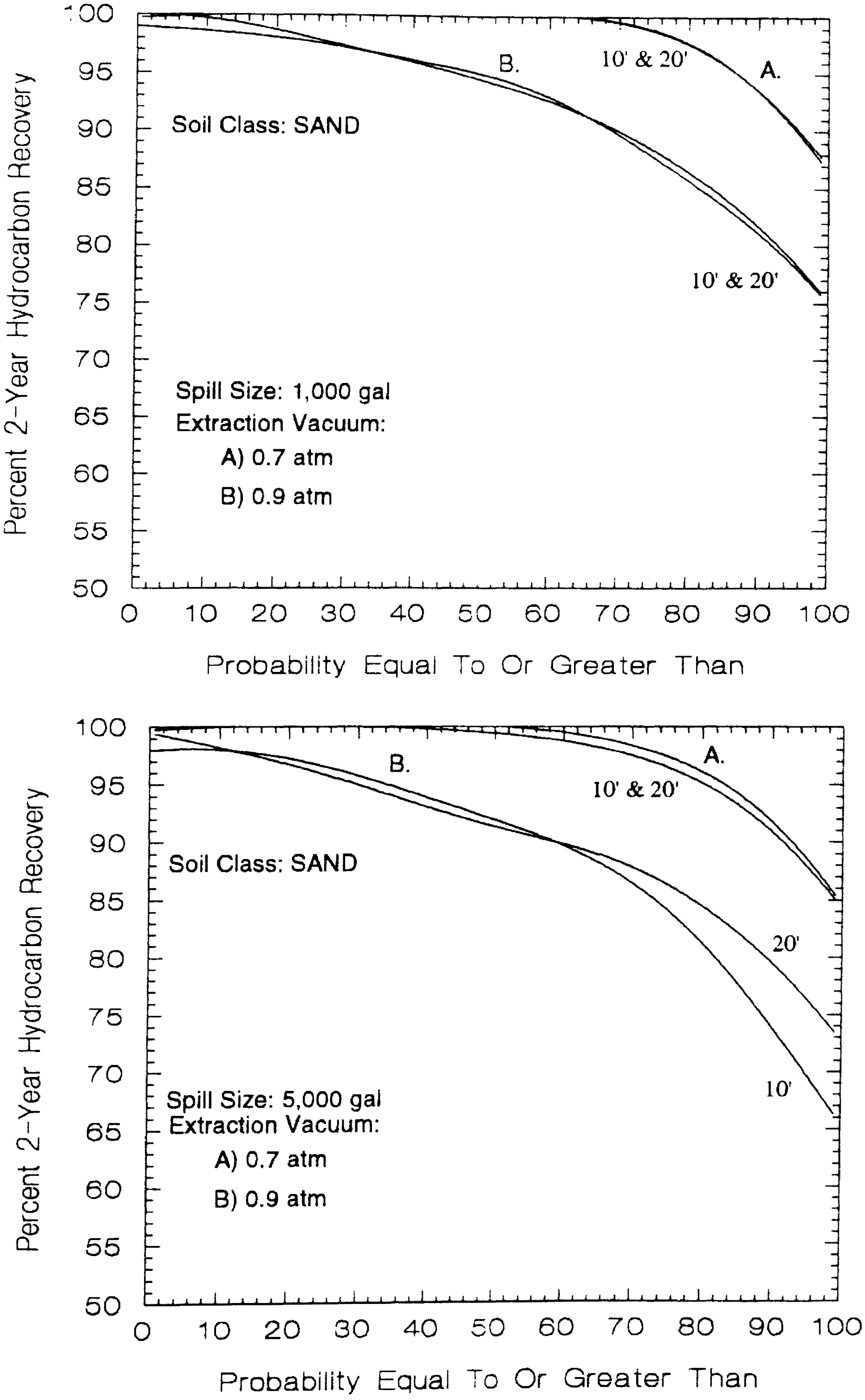


Figure 25. SAND SOIL control variable analysis plots for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery usin 0.7 and 0.9 atm vaccum at two spill sizes.

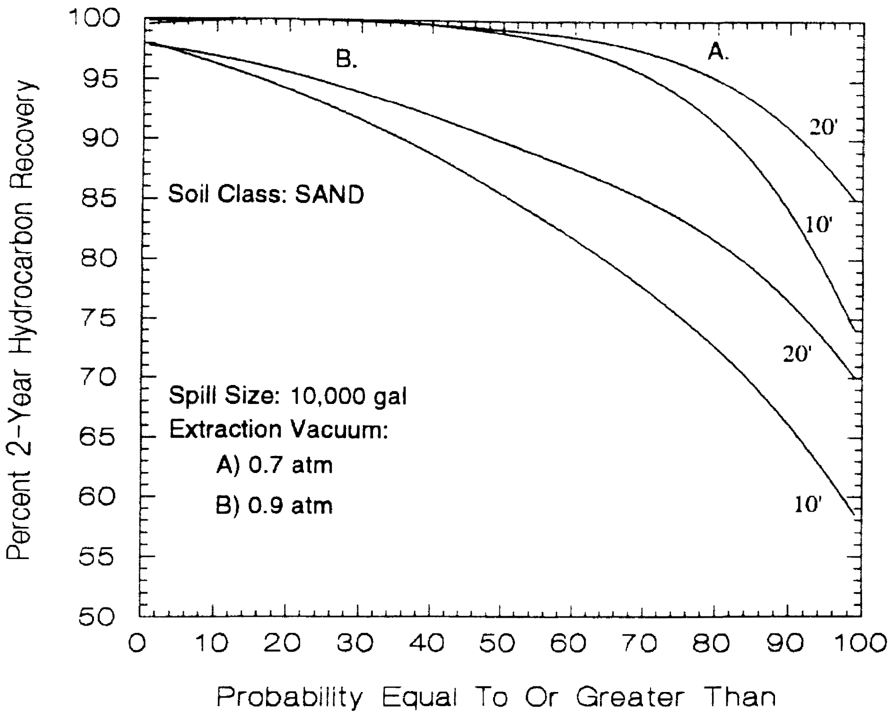


Figure 26. SAND SOIL control variable analysis for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery of a 10,000 gallon spill at two extraction vacuums.

spill sizes to assume some loss of accuracy. By using percent hydrocarbon recovery, probability of success might be evaluated with either spill size or TPH soil concentration. If an initial TPH concentration (or any other contaminant) is known, percent hydrocarbon recovery is simply based on the cleanup goal. For example, if the cleanup goal was 1,000 mg\kg TPH and field measurements indicated a level of 8,000 mg\kg, the amount of hydrocarbon that should be recovered to meet that goal was 87.5%. When spill size is known the initial TPH concentrations are as previously discussed. However, it should be pointed out again that these concentrations were calculated assuming a fixed radius of influence of 30 feet which led to the contaminated soil volume listed in Figure 2. Expressing venting success in terms of percent hydrocarbon recovery allows the user the flexibility to calculate a contaminated soil volume based on a different radius of influence to arrive at the required percent hydrocarbon for a given spill size. When operational parameters and spill values are similar, the use of these plots is a relatively straightforward process of simply selecting the appropriate plot for the variable of interest and reading directly from the fitted curve.

Interpolation of Intermediate Parameter Values

Intermediate values of spill size, screened interval, and extraction vacuum might be applied to the figures with an interpolation technique by assuming a linear relationship as in the example which follows: determine a 75 percent probability of the expected percent hydrocarbon recovery for a two year soil venting project for a 7,500 gallon gasoline spill in a sand soil with a 15 foot screen interval using a 0.8 atm extraction vacuum. The four probability plots which bracketed these operational and spill values are shown in Figures 23 and 24. The 75 percent hydrocarbon recovery at a spill size of 7,500 gallons, which was assumed to be located half the distance between the spill size curves for 5,000 and 10,000 gallons, were 96, 80, 86, and 87 percent hydrocarbon recovered respectively. Double interpolation required an initial interpolation between figures 23 and 24 at the new vacuum pressure of 0.8 atm., which are seen in equations 6 and 7.

$$X_2 = \frac{96-80}{0.7-0.9}(0.8-0.9)+80=88 \tag{6}$$

$$X_1 = \frac{97-86}{0.7-0.9}(0.8-0.9)+86=91.5 \tag{7}$$

The final interpolation between the above two values for the screened interval of 15 feet was calculated by equation 8:

$$X_3 = \frac{91.5-88.0}{20-10}(15-10)+88.0=89.8 \tag{8}$$

Therefore, at the stated operating conditions, there was a 75 percent probability that at least 89.8 percent of the gasoline spill would be recovered during the 2 year venting period.

The same interpolation technique can also be used by continuing to assume a linear relationship with the soil class probability plots for either spill size or TPH and hazardous constituent soil concentration.

Effect of Parameter Selection on Probability

Evaluation of Figures 15-21 indicated that venting success in sand soil was most sensitive to extraction vacuum for all spill size and contaminant thickness. As an example, for a 10,000 gallon spill size and 10 foot screened interval, the 50% probability percent of hydrocarbon recovery was 85% using 0.9 atm vacuum, compared to 99% when using a 0.7 atm vacuum (Figure 19). Figure 17 showed that, even at a smaller spill size of 1,000 gallons, there was a 5% difference of hydrocarbon recovery (approximately 200 mg\kg TPH). Generally, venting success was found to be less sensitivity to other parameters. Although the magnitude of that sensitivity varied mainly as a function of spill size. For instance as seen in Figure 20, the effect of contaminant thickness made very little difference in the percent hydrocarbon recovery at all probability levels for the 1,000 gallon spill size. This would indicate that soil venting would be equally effective for contaminated thickness up to 20 feet regardless of extraction vacuum. As spill size increases the difference in percent hydrocarbon recovery between the 10 and 20 foot thickness (Figures 20 and 21) become more apparent and as a result selection of extraction vacuum becomes more important to venting success.

Figure 17 may serve as an example of applying the figures to examine trade-offs in system design. Shown in that figure are the plots which compare the effect of extraction vacuum on recovery of a 1,000 gallon spill for 10 and 20 foot thickness. In the case of a 10 foot contaminant thickness with a cleanup goal of 1,000 mg\kg, the question becomes which extraction vacuum should be applied. Under the conditions for which the simulation was run (see Figure 2), initial TPH concentration was approximately 4,000 mg\kg based on a contaminated soil volume of about 16,000 cubic feet. To reduce TPH to 1,000 mg\kg, about 75% hydrocarbon recovery was required. Entering the plot and reading at an 80% probability level, the 0.9 atm extraction vacuum was expected to recover about 85% of the hydrocarbon compared to 97% for the 0.7 atm extraction vacuum. Since the use of either vacuum would recover more than the 75% of the hydrocarbon required by the cleanup goal, the optimal design option would be to choose the 0.9 atm extraction vacuum which may result in lower operating costs.

Application Of Screening Guidelines

To test the validity of these screening guidelines the same parameters used by Johnson et al. (1990a) to test his original model was used. Since the spill modelled originally by Johnson (1990a) was gasoline, the two pieces of information required to use the initial screening plots (soil class probabilities) are spill size or concentration and soil type. An initial soil gasoline concentration of 20,000 mg/kg was reported. Soil type based on other reported parameters was assumed to be a loamy sand. The probability of reducing TPH to 1,000 mg/kg in a two year period can be found by referring to the 5,000 gallon spill line on Figure 10. From figure 10 there is an approximate 26 percent chance that TPH will be at 1,000 mg/kg or less within 2-years. Johnson et al. (1990a) reported approximately 2,000 mg/kg TPH after 400 days of venting.

SUMMARY AND CONCLUSIONS

Summary

Soil vapor extraction has become a widely used and accepted method for removing hydrocarbon contamination from unsaturated soils. Successful applications of soil venting were found to be highly dependant on the air permeability of the contaminated soil. The most common approach to determining air permeability is lab or field testing which goes beyond the preliminary screening level. Numerical methods which require an estimate of air permeability are often used to screen applications and design soil venting systems. However, making adequate estimates of air permeability are often difficult without lab or field tests.

A regression method, developed and used in agricultural research to predict soil properties based on soil textural classifications was utilized to produce randomly generated soil properties. These soil properties allowed a normally distributed range of soil air permeabilities to be calculated for sand, loamy sand, sandy loam, and loam soils. Utilizing a Monte Carlo approach, predictions of the magnitude and the probability of occurrence of air permeability were made. These probability indexed air permeabilites were then used in a publicly available numerical model to evaluate the performance of soil venting within each soil type. Soil venting evaluations were conducted for a composite gasoline over a range of commonly encountered site and operational conditions was developed. In this manner a probability-based screening method to predict and quantify the success of soil venting based on soil textural classes was developed.

Conclusions

Using probability based nomographs as a process selection screening tool is a viable means to predict the efficiency of soil venting and could be used in the absence of site specific permeability data. These may serve as a quick screening method to predict and quantify expected hydrocarbon recovery from gasoline contaminated soils during soil venting without conducting expensive and sophisticated time-consuming field and/or laboratory testing. The decision as to what probability level is sufficient to be confident of predicted outcomes should ultimately be made by the user. A probability of 50 percent is the mean or average outcome and could serve as the division between recommending implementation and seeking additional data for further study. An important assumption that should be taken under consideration when using these plots is that the venting process was assumed to be 100 percent efficient. Reduction in efficiency under actual field conditions would reduce the amount of hydrocarbon recovered. Uncertainty in actual operating efficiency may be addressed by basing decisions on higher probabilities of success or lower than required cleanup goals.

Using the EPA criteria of 2 years or less to meet remediation goals, soil venting of spills in the 1,000 gallon range could be recommended in all four soils. At higher spill sizes soil venting does not appear to be a viable option for sandy loam or loam soils. Probability of venting success was found to be most dependant on extraction vacuum and least dependant on contaminant thickness. Higher extraction vacuums significantly improved the probability of successful cleanup especially for larger spill sizes. In some cases however, lower extraction vacuum was found to be as effective as a higher vacuum. Increased venting times do not significantly improve the probability of success in loam or sandy loam soils for spills in the 5,000 gallon size or larger.

Probability of venting success is improved, especially in less permeable loam and sandy loam soils when based on more volatile hazardous constituents. In these cases venting may become part of a multi-phase approach to site remediation.

Decisions regarding remediation selection must sometimes be made in situations where only minimal data is available. In these situations probability-based guidelines would be most useful in soils other than sands where questionable venting efficiencies are possible

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APPENDICES

APPENDIX A

COMPUTER PROGRAM TO GENERATE RANDOM SOIL PROPERTIES

Computer Program To Generate Random Soil Properties For Sand Soil

```
'==========================================================================
' BASIC PRGRAM TO GENERATE RANDOM VALUES FOR SOIL PARAMETERS
' (KS, QR, ALPHA, AND N) USING **SAND INPUT DATA**. Based on Carsel and Parrish
' paper "Developing Joint Probability Distributions of Soil Water Retention
' Characteristics"  Wat. Res. Res. vol. 24, no. 5, p. 755-769.
'==========================================================================
DIM T(10), AMU(4), X(4), Y(4), Z(4), A(4), B(4), TR$(4), TA(4), TB(4)
'-----------------------------------------------------------------------
'Load means variable limits, transformations, and truncated limits,
'  if any. [Note: Code truncated distributions as "LN*", "SB*", "SU*",
'  or "NO*"]
'-----------------------------------------------------------------------
DATA -0.394, 0.0, 70.0, "SB", 0., 0.
DATA -3.120, 0.0, 0.10, "LN", 0., 0.
DATA  0.378, 0.0, 0.25, "SB", 0., 0.
DATA  0.978, 1.5, 4.00, "LN", 0., 0.
'
FOR I = 1 TO 4
  READ AMU(I), A(I), B(I), TR$(I), TA(I), TB(I)
  NEXT I
-----------------------------------------------------------------------
'Load factored covariance matrix T
'-----------------------------------------------------------------------
DATA 1.04,  -0.109, 0.328,  0.081
DATA         0.182, 0.258, -0.047
DATA                0.143, -0.011
DATA                        0.017
'
FOR I = 1 TO 10
  READ T(I)
  NEXT I
'-----------------------------------------------------------------------
'Get number to generate and open output file
'-----------------------------------------------------------------------
INPUT "Enter number of vectors to generate . . .", N
INPUT "Enter random number seed . . . . . . . . ", ISEED
'
RANDOMIZE ISEED
'
OPEN "MCARLO.SAN" FOR OUTPUT AS 1
-----------------------------------------------------------------------
'Print headings
'-----------------------------------------------------------------------
PRINT #1, TAB(6); "KS,";
PRINT #1, TAB(17); "QR,";
PRINT #1, TAB(32); "ALPHA,";
PRINT #1, TAB(42); "N,"
'-----------------------------------------------------------------------
'Begin Loop
'-----------------------------------------------------------------------
FOR L = 1 TO N
```

```
'--------------------------------------------------------------------------
'Generate independant normal random deviates
'--------------------------------------------------------------------------
100 FOR J = 1 TO 4
      Z(J) = -6!
      FOR K = 1 TO 12
        Z(J) = Z(J) + RND      'RND = uniform (0,1) deviate
        NEXT K
      NEXT J
--------------------------------------------------------------------------
'Apply linear transforms to produce correlated values
'--------------------------------------------------------------------------
Y(1) = AMU(1) + T(1) * Z(1)
Y(2) = AMU(2) + T(2) * Z(1) + T(5) * Z(2)
Y(3) = AMU(3) + T(3) * Z(1) + T(6) * Z(2) + T(8) * Z(3)
Y(4) = AMU(4) + T(4) * Z(1) + T(7) * Z(2) + T(9) * Z(3) + T(10) * Z(4)
'--------------------------------------------------------------------------
'Check limits for any truncated distributions
'--------------------------------------------------------------------------
IF MID$(TR$(1), 3, 1) = "*" THEN IF Y(1) < TA(1) OR Y(1) > TB(1) THEN 100
IF MID$(TR$(2), 3, 1) = "*" THEN IF Y(2) < TA(2) OR Y(2) > TB(2) THEN 100
IF MID$(TR$(3), 3, 1) = "*" THEN IF Y(3) < TA(3) OR Y(3) > TB(3) THEN 100
IF MID$(TR$(4), 3, 1) = "*" THEN IF Y(4) < TA(4) OR Y(4) > TB(4) THEN 100
'--------------------------------------------------------------------------
'Inverse transform correlated normals to get random deviates
'   for KS, QR, ALPHA, N
'--------------------------------------------------------------------------
FOR J = 1 TO 4
  U = EXP(Y(J))
  IF MID$(TR$(J), 1, 2) = "LN" THEN X(J) = U ELSE IF MID$(TR$(J), 1, 2) = "SB" THEN X(J) =
(B(J) * U + A(J)) / (1! + U) ELSE IF MID$(TR$(J), 1, 2) = "SU" THEN X(J) = A(J) + .5 * (B(J) -
A(J)) * (U - 1! / U) ELSE X(J) = Y(J)
  NEXT J
--------------------------------------------------------------------------
'Ensure that values are within defined limits
'--------------------------------------------------------------------------
IF X(1) < A(1) OR X(1) > B(1) THEN 100
IF X(2) < A(2) OR X(2) > B(2) THEN 100
IF X(3) < A(3) OR X(3) > B(3) THEN 100
IF X(4) < A(4) OR X(4) > B(4) THEN 100
'--------------------------------------------------------------------------
'Output random vector (KS, QR, ALPHA, N) and close loop
'--------------------------------------------------------------------------
PRINT #1, X(1); ","; X(2); ","; X(3); ","; X(4)
'
NEXT L
--------------------------------------------------------------------------
'Finish
-----------------------------------------------------------------
CLOSE #1
END
```

APPENDIX B

SAMPLE SPREADSHEET OF AIR PERMEABILITY CALCULATIONS

VAPOR EXTRACTION MONTE CARLO SIMULATION

SOIL DATA

Soil Class: SAND
Simulation Number: SD-1

Randomized Soil Properties						**Calculated Soil Properties**			
Sat. Hyd. Cond. (cm/hr)	*Residual Water Content*	*ALPHA*	*N*	*M*	*Saturated Water Content*	*Field Capacity*	*Intrinsic Perm (cm^2)*	*Relative Perm to Air*	**AIR PERM (darcy)**
7.863	0.052	0.105	2.324	0.570	0.525	0.056	2.23E-08	0.469	**1.046**
25.894	0.045	0.142	2.608	0.617	0.520	0.045	7.34E-08	0.474	**3.481**
32.745	0.052	0.163	2.676	0.626	0.418	0.053	9.28E-08	0.366	**3.394**
20.625	0.035	0.106	2.727	0.633	0.404	0.036	5.85E-08	0.368	**2.149**
23.220	0.059	0.176	2.330	0.571	0.468	0.061	6.58E-08	0.407	**2.678**
23.728	0.039	0.132	2.683	0.627	0.498	0.040	6.73E-08	0.459	**3.086**
39.326	0.040	0.164	2.771	0.639	0.464	0.040	1.11E-07	0.423	**4.719**
17.646	0.038	0.111	2.649	0.623	0.555	0.039	5.00E-08	0.516	**2.578**
12.034	0.052	0.136	2.399	0.583	0.453	0.054	3.41E-08	0.399	**1.363**
49.161	0.034	0.180	2.889	0.654	0.379	0.034	1.39E-07	0.345	**4.802**
34.083	0.046	0.157	2.654	0.623	0.427	0.046	9.66E-08	0.381	**3.684**
32.197	0.048	0.177	2.579	0.612	0.441	0.049	9.13E-08	0.392	**3.579**
57.822	0.038	0.192	2.900	0.655	0.474	0.038	1.64E-07	0.437	**7.155**
16.784	0.053	0.142	2.401	0.584	0.410	0.054	4.76E-08	0.355	**1.690**
7.831	0.050	0.125	2.337	0.572	0.469	0.053	2.22E-08	0.417	**0.925**
16.055	0.048	0.126	2.528	0.604	0.415	0.049	4.55E-08	0.366	**1.664**
23.682	0.061	0.165	2.491	0.599	0.463	0.062	6.71E-08	0.401	**2.694**
27.013	0.043	0.144	2.625	0.619	0.435	0.044	7.66E-08	0.391	**2.997**
24.652	0.036	0.133	2.795	0.642	0.439	0.037	6.99E-08	0.402	**2.808**
7.226	0.043	0.112	2.393	0.582	0.383	0.045	2.05E-08	0.337	**0.691**
8.214	0.066	0.120	2.256	0.557	0.509	0.070	2.33E-08	0.439	**1.023**
60.784	0.051	0.202	2.925	0.658	0.478	0.051	1.72E-07	0.427	**7.362**
38.042	0.040	0.149	2.778	0.640	0.517	0.040	1.08E-07	0.477	**5.149**
19.803	0.034	0.104	2.694	0.629	0.456	0.035	5.61E-08	0.420	**2.358**
5.393	0.068	0.120	2.174	0.540	0.524	0.073	1.53E-08	0.451	**0.689**
29.086	0.057	0.167	2.506	0.601	0.404	0.058	8.24E-08	0.346	**2.854**
39.862	0.053	0.173	2.651	0.623	0.518	0.054	1.13E-07	0.465	**5.252**
24.216	0.048	0.144	2.654	0.623	0.321	0.048	6.86E-08	0.273	**1.871**
7.864	0.039	0.101	2.536	0.606	0.516	0.041	2.23E-08	0.475	**1.058**
20.130	0.054	0.167	2.437	0.590	0.423	0.055	5.71E-08	0.368	**2.102**
14.601	0.040	0.112	2.601	0.616	0.406	0.041	4.14E-08	0.365	**1.512**
30.784	0.050	0.170	2.498	0.600	0.426	0.051	8.73E-08	0.375	**3.269**
22.163	0.045	0.129	2.632	0.620	0.421	0.045	6.28E-08	0.375	**2.358**
38.287	0.036	0.155	2.832	0.647	0.479	0.036	1.09E-07	0.443	**4.803**
12.307	0.073	0.152	2.162	0.537	0.443	0.077	3.49E-08	0.366	**1.275**
54.941	0.062	0.215	2.651	0.623	0.405	0.062	1.56E-07	0.342	**5.328**
23.693	0.042	0.157	2.582	0.613	0.366	0.043	6.72E-08	0.324	**2.173**
31.955	0.034	0.142	2.845	0.648	0.458	0.034	9.06E-08	0.424	**3.843**
28.853	0.054	0.170	2.537	0.606	0.376	0.055	8.18E-08	0.321	**2.627**
31.723	0.039	0.138	2.813	0.644	0.485	0.039	8.99E-08	0.446	**4.010**

Alpha, N, and M are derived van Genuchten empirical constants

APPENDIX C

REPRESENTATIVE VENTING MODEL OUTPUT

```
 + + + + + + + + + + + + + + + + + + + + + + + + + + + + +
 +                   VENTING                  +
 +                                       +
 +           COPYRIGHT 1991 VERSION 2.0              +
 +                                       +
 +    Environmental Systems and Technologies Inc.      +
 +                                       +
 +           BLACKSBURG, VA 24062, U.S.A.            +
 +                                       +
 +                                       +
 +                                       +
 + + + + + + + + + + + + + + + + + + + + + + + + + + + + +

TITLE: ls16-t11
------


  TOTAL MASS OF SPILL   = .14194E+05 [kg]
  AIR FLOW RATE         = .15249E+06 [L/day]
  TEMPERATURE           = .16000E+02 [c]
  STARTING TIME STEP    = .10000E-04 [days]
  MAXIMUM TIME STEP     = .36500E+03 [days]
  TOTAL SIMULATION TIME = .21900E+04 [days]
  TIME WEIGHTING FACTOR = .50000E+00 [-]
  EFFICIENCY FACTOR     = .10000E+01 [-]
  SOIL VOLUME           = .91274E+03 [m^3]
  FRAC. ORGANIC CARBON  = .50000E-02 [-]
  VOL. WATER CONTENT    = .14000E+00 [-]
  BULK DENSITY          = .13383E+01 [g/cm^3]
  AIR FILLED POROSITY   = .35500E+00 [-]


SPECIES                  MOL.   -|- VAP  -|- BOILING- |-SOLUB   -|- KOC -|
                        WEIGHT  PRESSURE   TEMP      ILITY

                        gm/mole    atm     deg. c     mg/L      g/g

 1 n-hexane              .8620E+02 .1600E+00 .6900E+02 .1300E+02 .8710E+04
 2 benzene               .7810E+02 .1000E+00 .8000E+02 .1780E+04 .1350E+03
 3 toluene               .9210E+02 .2900E-01 .1110E+03 .5150E+03 .4900E+03
 4 p-xylene              .1062E+03 .8600E-02 .1380E+03 .1980E+03 .1413E+04
 5 m-xylene              .1062E+03 .8000E-02 .1390E+03 .1620E+03 .1585E+04
 6 o-xylene              .1062E+03 .6600E-02 .1440E+03 .1750E+03 .5890E+03
 7 light-end             .7830E+02 .8440E+00 .4160E+02 .4500E+02 .8806E+04
 8 ethylbenzene          .1062E+03 .9200E-02 .1360E+03 .1520E+03 .1410E+04
 9 mtbe                  .8820E+02 .3280E+00 .5520E+02 .5100E+05 .1700E+02
 10 heavy-end            .1311E+03 .2630E-02 .1749E+03 .3200E+02 .6003E+05
SPECIES                  SPECIES   WELL GAS  EQUIL. GAS  SPECIES MASS
                        MASS      CONCEN. .  CONCEN.   PER SOIL MASS
                        [g]      [g/m^3]   [g/m^3]     [mg/kg]

 1 n-hexane             .5252E+06  .0000E+00  .0000E+00  .4299E+03
 2 benzene              .2555E+06  .0000E+00  .0000E+00  .2092E+03
 3 toluene              .1036E+07  .0000E+00  .0000E+00  .8483E+03
 4 p-xylene             .6671E+06  .0000E+00  .0000E+00  .5462E+03
 5 m-xylene             .4684E+06  .0000E+00  .0000E+00  .3835E+03
 6 o-xylene             .2981E+06  .0000E+00  .0000E+00  .2440E+03
 7 light-end            .5493E+07  .0000E+00  .0000E+00  .4497E+04
 8 ethylbenzene         .2697E+06  .0000E+00  .0000E+00  .2208E+03
 9 mtbe                 .7523E+06  .0000E+00  .0000E+00  .6159E+03
```

```
10 heavy-end              .4428E+07  .0000E+00  .0000E+00  .3626E+04

 TIME                             =     .0000  [days]
 TOTAL MASS OF HYDROCARBON                 =  14194E+05  [kg]
 TOTAL MASS IN VAPOR PHASE               = .00000E+00  [kg]
 TOTAL MASS IN OIL PHASE               = .00000E+00  [kg]
 TOTAL MASS IN WATER PHASE               = .00000E+00  [kg]
 TOTAL MASS IN SOLID PHASE              = .00000E+00  [kg]
 HYDROCARBON MASS PER SOIL MASS            = .11620E+05  [mg/kg]

 TIME                             =     .0000  [days]
 TOTAL MASS OF HYDROCARBON                 = .14194E+05  [kg]
 TOTAL MASS IN VAPOR PHASE               = .43937E+03  [kg]
 TOTAL MASS IN OIL PHASE               = .11103E+05  [kg]
 TOTAL MASS IN WATER PHASE               = .28025E+03  [kg]
 TOTAL MASS IN SOLID PHASE              = .25329E+04  [kg]
 CHANGE IN HYDROCARBON MASS FOR TIME STEP  = .14091E-04  [%]
 CUMULATIVE CHANGE IN HYDROCARBON          = .14091E-04  [%]
 HYDROCARBON MASS PER SOIL MASS            = .11620E+05  [mg/kg]

SPECIES                   SPECIES   WELL GAS   EQUIL. GAS  SPECIES MASS
                        MASS      CONCEN. .  CONCEN.    PER SOIL MASS
                        [g]      [g/m^3]   [g/m^3]     [mg/kg]

1 n-hexane                .5252E+06  .7562E-06  .7562E-06  .4299E+03
2 benzene                 .2555E+06  .3426E-06  .3426E-06  .2092E+03
3 toluene                .1036E+07  .0000E+00  .0000E+00  .8483E+03
4 p-xylene               .6671E+06  .0000E+00  .0000E+00  .5462E+03
5 m-xylene                .4684E+06  .0000E+00  .0000E+00  .3835E+03
6 o-xylene               .2981E+06  .0000E+00  .0000E+00  .2440E+03
7 light-end              .5493E+07  .3297E-04  .3297E-04  .4497E+04
8 ethylbenzene            .2697E+06  .0000E+00  .0000E+00  .2208E+03
9 mtbe                   .7523E+06  .1548E-05  .1548E-05  .6159E+03
10 heavy-end              .4428E+07  .0000E+00  .0000E+00  .3626E+04

SPECIES                           SPECIES MASS [g] IN
                        GAS       OIL       WATER       SOLID

1 n-hexane                .7658E+04  .4970E+06  .8063E+02  .2115E+05
2 benzene                 .2154E+04  .2260E+06  .5541E+04  .2252E+05
3 toluene                .2565E+04  .9463E+06  .5691E+04  .8397E+05
4 p-xylene                .4828E+03  .6144E+06  .1232E+04  .5242E+05
5 m-xylene                .3168E+03  .4343E+06  .7125E+03  .3400E+05
6 o-xylene               .1733E+03  .2886E+06  .5115E+03  .9071E+04
7 light-end              .4113E+06  .4387E+07  .2712E+04  .7191E+06
8 ethylbenzene            .2128E+03  .2530E+06  .3895E+03  .1654E+05
9 mtbe                   .1378E+05  .4222E+06  .2626E+06  .1344E+06
10 heavy-end              .7230E+03  .3034E+07  .7965E+03  .1440E+07
*********************************************
     end of initial conditions
*********************************************

TIME                            =  365.0000  [days]
TOTAL MASS OF HYDROCARBON                 = .61414E+04  [kg]
TOTAL MASS IN VAPOR PHASE               = .32955E+03  [kg]
TOTAL MASS IN OIL PHASE               = .66017E+04  [kg]
TOTAL MASS IN WATER PHASE               = .19159E+02  [kg]
TOTAL MASS IN SOLID PHASE              = .28594E+04  [kg]
CHANGE IN HYDROCARBON MASS FOR TIME STEP  = .56732E+02  [%]
CUMULATIVE CHANGE IN HYDROCARBON          = .56732E+02  [%]
HYDROCARBON MASS PER SOIL MASS            = .50278E+04  [mg/kg]
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APPENDIX D

GASOLINE COMPONENT MASS BALANCE CALCULATIONS

Physio-Chemical Characteristics and Composition of the Light Ends of a Composite Gasoline.

Represenative "Light-End" Chemical Component	Mole Weight (g/mole)	Normalized Mass Conc. (% w/w)	Mixture Mass Fraction	Mixture Mole Fraction	Vapour Press. (atm)	Boiling Point Temp (deg C)	Water Solubility (mg/L)	Kow	Mole Fraction Weight		Mole Fraction Vapour Press.	Mole Fraction Boiling Point Temp.	Mole Fraction Water Sol.	Mole Fraction Kow	Mole Fraction Weight
trans-2-butene	56.10	1.81	0.0003	0.025	1.97	1	430	204	1.42		0.04970	0.025	10.847	5.146	1.41518589
isobutane	58.10	2.58	0.0004	0.035	2.93	-12	49	537	2.02		0.10195	-0.418	1.705	18.686	2.02169413
n-butane	58.10	13.69	0.0024	0.184	2.11	-1	61	946	10.71		0.38913	-0.184	11.250	174.464	10.7149789
3-methyl-1-butene	70.10	0.15	0.0000	0.002	0.96	21	130	708	0.12		0.00166	0.036	0.225	1.225	0.12130165
2-methyl-2-butene	70.10	1.14	0.0002	0.013	0.51	38	155	525	0.89		0.00647	0.482	1.967	6.662	0.88954542
isopentane	72.20	17.59	0.0024	0.191	0.78	28	48	1862	13.77		0.14874	5.339	9.153	355.063	13.767737
n-pentane	72.20	12.66	0.0018	0.137	0.57	36	40	2511	9.91		0.07821	4.939	5.488	344.525	9.90630125
3,3-dimethyl-1-butene	84.20	1.27	0.0002	0.012	0.47	41	23	1350	0.99		0.00553	0.482	0.271	15.883	0.99063012
2,3-dimethylbutane	86.20	16.27	0.0019	0.148	0.26	57	20	4786	12.74		0.03842	8.422	2.955	707.166	12.736673
2-methylpentane	86.20	6.97	0.0008	0.063	0.21	60	14	6457	5.46		0.01330	3.799	0.887	408.886	5.45857416
2,2-dimethylpentane	100.20	3.36	0.0003	0.026	0.11	79	4.4	16600	2.63		0.00289	2.072	0.115	435.411	2.62820237
2,3-dimethylpentane	100.20	8.78	0.0009	0.069	0.072	90	5.3	16600	6.87		0.00494	6.174	0.364	1138.767	6.87376005
n-heptane	100.20	1.63	0.0002	0.013	0.046	98	3	30000	1.27		0.00058	1.246	0.038	381.338	1.2736673
2,2,4-trimethylpentane	114.20	3.10	0.0003	0.021	0.051	99	2.2	42660	2.43		0.00108	2.103	0.047	906.257	2.42603296
2,2-dimethylhexane	114.20	1.42	0.0001	0.010	0.035	107	1.5	57544	1.11		0.00034	1.042	0.015	560.289	1.11193177
2,3,4-trimethylpentane	114.20	3.10	0.0003	0.021	0.028	114	1.8	42685	2.43		0.00059	2.422	0.038	906.788	2.42603296
2-methylheptane	114.20	4.13	0.0004	0.028	0.021	116	0.9	77625	3.23		0.00059	3.286	0.025	2198.725	3.23471061
n-octane	114.20	0.34	0.0000	0.002	0.014	126	0.7	104700	0.26		0.00003	0.290	0.002	240.957	0.26282024
Summations		*100.00*	*78.2598*	*1.000*	-	-	-	-	-	100.00					
Mole-fraction weighted averages		-	-	-	*0.844*	*41.56*	*45.39*	*8806*	*78.26*						
Original mixture concentration (%)		38.71								Mole-fraction weighted averages	**0.844**	**41.56**	**45.39**	**8806.24**	**78.26**

Data summary sheet showing composition mole-weighted fractions of light end components in a composite gasoline.

Physio-Chemical Characteristics and Composition of the Heavy Ends of a Composite Gasoline.

Represenative "Heavy-End" Chemical Component	Mole Weight (g/mole)	Normalized Mass Conc. (% w/w)	Mixture Mass Fraction	Mixture Mole Fraction	Vapour Press. (atm)	Boiling Point Temp (deg C)	Water Solubility (mg/L)	Kow	Mole Fraction Weight		Mole Fraction Vapour Press.	Mole Fraction Boiling Point Temp.	Mole Fraction Water Sol.	Mole Fraction Kow	Mole Fraction Weight
n-propylbenzene	120.20	20.52	0.0017	0.224	0.0033	159	60	4786	26.89		0.00074	35.577	13.425	1070.88	26.895
1,3,5-trimethylbenzene	120.20	11.54	0.0010	0.126	0.0024	165	73	12883	15.13		0.00030	20.767	9.188	1621.46	15.128
1,2,4-trimethylbenzene	120.20	6.73	0.0006	0.073	0.0019	169	57	12883	8.82		0.00014	12.408	4.185	945.85	8.825
napthalene	128.20	1.54	0.0001	0.016	0.00014	218	33	1738	2.02		0.00000	3.430	0.519	27.35	2.017
2,4,4-trimethylhexane	128.30	2.79	0.0002	0.028	0.013	131	1.4	147911	3.66		0.00037	3.733	0.040	4214.87	3.656
3,3,4-trimethylhexane	128.30	8.98	0.0007	0.092	0.0073	140	1.4	147911	11.77		0.00067	12.840	0.128	13565.10	11.767
methylpropylbenzene	134.20	9.65	0.0007	0.094	0.001	182	6.8	33884	12.65		0.00009	17.154	0.641	3193.74	12.649
dimethylethylbenzene	134.20	8.34	0.0006	0.081	0.0007	190	21	44668	10.93		0.00006	15.469	1.710	3636.71	10.926
1,2,4,5-tetramethylbenzen	134.20	4.17	0.0003	0.041	0.00046	196	3.5	12883	5.46		0.00002	7.979	0.142	524.44	5.463
1,2,3,4-tetramethylbenzen	134.20	4.17	0.0003	0.041	0.00033	205	21	12883	5.46		0.00001	8.345	0.855	524.44	5.463
methylnapthalene	142.20	0.74	0.0001	0.007	0.00005	241	27	7943	0.97		0.00000	1.638	0.184	53.99	0.967
2,2,4-trimethylheptane	142.30	3.53	0.0002	0.032	0.0053	149	0.8	389000	4.62		0.00017	4.840	0.026	12636.55	4.623
1,2,4-trimethyl-5-ethylbe	148.20	9.94	0.0007	0.088	0.00029	210	7	204000	13.03		0.00003	18.460	0.615	17932.25	13.027
n-dodecane	170.30	7.37	0.0004	0.057	0.0004	216	0.004	1537	9.67		0.00002	12.259	0.000	87.23	9.665
Summations		*100.00*	*131.071*	*1.000*	-	-	-	-	-						
Mole-fraction weighted averages		-	-	-	*0.00263*	*174.9*	*31.66*	*60035*	*131.07*						
Original mixture concentration (%)		31.19								Mole-fraction weighted averages	**0.00263**	**174.90**	**31.66**	**60034.00**	**131.071**

Data summary sheet showing composition mole-weighted fractions of high end components in a composite gasoline.

APPENDIX E

SUMMARY OF VENTING SIMULATION OUTPUT FOR SAND SOILS

APPENDIX E

SOIL VENTING SIMULATIONS DATA SUMMARY

SAND SOIL

Simulation SD-1

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.42	99.3	29.5	0.0	0.0	95.8	186.9	0.0	0
10	5.78	97.5	98.5	0.0	0.0	91.6	329.4	0.0	0
20	4.82	98.1	93.2	0.0	0.0	92.7	353.8	0.0	0
30	4.07	96.6	155.6	0.0	0.0	90.2	448.3	0.0	0
40	3.44	96.4	176.9	0.0	0.0	89.4	518.9	0.0	0
50	2.88	92.2	307.3	0.0	0.0	84.9	596.3	0.0	0
60	2.50	94.1	311.1	0.0	0.0	86.9	690.1	0.0	0
70	2.12	89.4	429.5	0.0	0.0	81.8	739.2	0.9	0
80	1.64	86.7	532.8	0.0	0.0	79.6	818.8	2.1	0
90	1.15	83.8	787.9	0.0	0.0	77.3	1102.7	10.7	0
99	0.433	74.4	1019.1	23.1	0.0	69.0	1234.4	121.7	1
Initial Soil Concentration:			4242.0	1278.0	81.0				

Simulation SD-2

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	0.5 YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.9	1.0	0.0	0.0	98.8	60.1	0.0	0
10	5.785	99.9	7.0	0.0	0.0	96.5	139.7	0.0	0
20	4.818	99.9	10.0	0.0	0.0	95.5	187.1	0.0	0
30	4.073	99.9	20.0	0.0	0.0	94.2	237.9	0.0	0
40	3.436	99.9	31.0	0.0	0.0	94.8	294.0	0.1	0
50	2.882	99.9	35.0	0.0	0.0	91.5	373.0	0.0	0
60	2.497	99.9	40.0	0.0	0.0	90.0	433.5	0.0	0
70	2.118	99.9	45.0	0.0	0.0	87.4	507.3	0.1	0
80	1.643	99.9	50.0	0.0	0.0	84.4	622.2	0.3	0
90	1.148	96.4	156.0	0.0	0.0	81.7	784.5	4.4	0
99	0.433	84.7	608.9	0.8	0.0	71.8	1079.0	55.0	0
Initial Soil Concentration:			4242.0	1278.0	81.0				

Simulation SD-3

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.9	20.0	0.0	0.0	95.8	93.0	0.0	0
10	5.785	99.9	40.0	0.0	0.0	92.4	148.1	0.0	0

20	4.818	99.9	60.0	0.0	0.0	91.9	180.4	0.0	0
30	4.073	95.7	80.7	0.0	0.0	88.5	218.5	0.0	0
40	3.436	94.5	108.6	0.0	0.0	86.9	258.7	0.0	0
50	2.882	96.0	83.1	0.0	0.0	88.9	232.7	0.0	0
60	2.497	95.0	146.4	0.0	0.0	84.4	324.0	0.0	0
70	2.118	89.0	221.3	0.0	0.0	81.3	351.3	0.0	0
80	1.643	83.7	275.0	0.0	0.0	78.9	440.0	0.4	0
90	1.148	84.4	358.6	0.0	0.0	77.8	512.3	2.7	0
99	0.433	74.3	503.0	11.6	0.0	70.1	595.0	24.4	0
Initial Soil Concentration:			2121.0	639.0	40.0				

Simulation SD-4

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	0.5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.9	0.5	0.0	0.0	99.1	23.0	0.0	0
10	5.785	99.9	1.0	0.0	0.0	98.1	45.8	0.0	0
20	4.818	99.9	10.0	0.0	0.0	95.8	79.5	0.0	0
30	4.073	99.9	20.0	0.0	0.0	94.3	116.1	0.0	0
40	3.436	99.9	30.0	0.0	0.0	93.6	141.1	0.0	0
50	2.882	99.9	40.0	0.0	0.0	89.4	196.6	0.0	0
60	2.497	99.9	50.0	0.0	0.0	88.3	217.0	0.0	0
70	2.118	99.9	75.7	0.0	0.0	87.5	261.0	0.0	0
80	1.643	99.9	124.3	0.0	0.0	81.7	383.4	0.0	0
90	1.148	95.6	83.9	0.0	0.0	80.9	366.3	0.0	0

99	0.433	86.1	259.4	0.0	0.0	74.0	484.6	0.0	0
Initial Soil Concentration:			2121.0	639.0	40.0				

Simulation SD-5

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	97.7	466.0	0.0	0.0	99.9	20.0	0.0	0
10	5.785	98.6	331.0	0.0	0.0	99.8	25.0	0.0	0
20	4.818	97.2	699.8	0.0	0.0	99.7	39.2	0.0	0
30	4.073	96.2	935.5	0.0	0.0	99.6	86.1	0.0	0
40	3.436	92.6	1474.0	0.0	0.0	98.6	286.0	0.0	0
50	2.882	90.7	1844.0	0.0	0.0	97.7	458.0	0.0	0
60	2.497	90.4	2070.9	0.4	0.0	97.5	534.7	0.0	0
70	2.118	87.2	2533.8	0.8	0.0	95.5	898.2	0.0	0
80	1.643	85.2	2928.0	1.0	0.0	92.1	1576.0	0.0	0
90	1.148	70.3	5904.8	115.4	0.0	88.1	2360.0	0.0	0
99	0.433	67.3	6300.7	733.7	0.0	80.2	3937.3	8.3	0
Initial Soil Concentration:			19890.0	5986.0	358.0				

Simulation SD-6

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.9	1.0	0.0	0.0	99.1	188.8	0.0	0
10	5.785	99.9	10.0	0.0	0.0	98.2	347.3	0.0	0
20	4.818	99.9	20.0	0.0	0.0	97.4	511.2	0.0	0
30	4.073	99.9	30.0	0.0	0.0	96.5	704.1	0.0	0
40	3.436	99.9	40.0	0.0	0.0	95.3	941.0	0.0	0
50	2.882	99.8	54.6	0.0	0.0	94.8	1281.0	0.0	0
60	2.497	99.5	102.8	0.0	0.0	94.2	1151.5	0.0	0
70	2.118	98.3	324.0	0.0	0.0	92.6	1466.2	0.0	0
80	1.643	97.7	534.2	0.0	0.0	89.9	2016.1	0.0	0
90	1.148	95.1	1026.4	0.0	0.0	85.9	2819.2	1.6	0
99	0.433	83.1	3392.9	3.9	0.0	75.7	4825.4	353.2	0
Initial Soil Concentration:			19890.0	5986.0	358.0				

Simulation SD-7

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.5	65.6	0.0	0.0	99.9	6.0	0.0	0
10	5.785	97.8	220.9	0.0	0.0	99.8	21.0	0.0	0

20	4.818	96.9	323.6	0.0	0.0	99.6	42.0	0.0	0
30	4.073	95.7	425.7	0.0	0.0	99.2	77.0	0.0	0
40	3.436	92.0	660.3	0.0	0.0	98.0	161.8	0.0	0
50	2.882	90.3	888.4	0.0	0.0	97.4	238.1	0.0	0
60	2.497	89.3	1040.3	0.0	0.0	96.8	312.8	0.0	0
70	2.118	90.8	1109.3	0.0	0.0	97.4	311.0	0.0	0
80	1.643	83.9	1605.5	0.5	0.0	92.8	720.2	0.0	0
90	1.148	81.7	2051.5	2.5	0.0	90.5	1069.0	0.0	0
99	0.433	72.1	2779.0	147.0	0.0	81.0	1893.6	1.6	0
Initial Soil Concentration:			19890.0	5986.0	358.0				

Simulation SD-8

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	100.0	2.1	0.0	0.0	99.6	40.5	0.0	0
10	5.785	99.9	7.2	0.0	0.0	99.1	88.9	0.0	0
20	4.818	99.8	15.6	0.0	0.0	98.6	143.9	0.0	0
30	4.073	99.7	29.8	0.0	0.0	97.9	213.2	0.0	0
40	3.436	99.5	53.1	0.0	0.0	97.0	301.4	0.0	0
50	2.882	99.1	91.6	0.0	0.0	95.8	416.1	0.0	0
60	2.497	98.6	135.4	0.0	0.0	94.7	523.2	0.0	0
70	2.118	98.0	203.7	0.0	0.0	93.3	664.0	0.0	0
80	1.643	96.3	363.6	0.0	0.0	90.5	942.3	0.3	0

90	1.148	93.5	651.3	0.0	0.0	86.8	1309.9	0.9	0
99	0.433	83.2	1670.8	0.0	0.0	77.5	2238.2	28.2	0
Initial Soil Concentration:			9945.0	2993.0	179.0				

Simulation SD-9

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	98.1	771.3	0.0	0.0	84.3	6246.4	0.4	0
10	5.785	96.2	1520.8	3.9	0.0	80.2	7887.4	177.4	0
20	4.818	93.9	2423.4	22.0	0.0	76.5	9364.0	748.0	0
30	4.073	91.8	3266.0	1.3	0.0	73.5	10535.0	1252.0	0
40	3.436	88.6	4519.0	147.7	0.0	71.0	11536.0	1714.0	0
50	2.882	85.5	5760.7	76.9	0.0	68.8	12431.0	2151.0	0
60	2.497	81.2	7439.6	311.7	0.0	66.8	13207.0	2607.0	0
70	2.118	78.1	8712.0	1127.0	0.0	60.7	15625.0	4255.0	0
80	1.643	73.5	10566.0	1829.0	0.0	58.5	16494.0	4884.0	0
90	1.148	67.9	12754.0	2879.0	0.0	56.1	17466.0	5616.0	0
99	0.433	57.2	17029.0	5564.0	49.1	50.4	19729.0	7519.0	327.2
Initial Soil Concentration:			39765.0	11975.0	716.0				

Simulation SD-10

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	99.9	5.9	0.0	0.0	99.2	309.5	0.0	0
10	5.785	99.7	21.7	0.0	0.0	98.4	624.1	0.0	0
20	4.818	99.5	53.1	0.0	0.0	97.4	1027.0	0.0	0
30	4.073	99.4	111.6	0.0	0.0	94.9	2000.0	0.0	0
40	3.436	99.2	224.8	0.0	0.0	92.9	2792.0	0.0	0
50	2.882	98.4	636.1	0.0	0.0	89.0	4357.0	0.0	0
60	2.497	97.6	971.3	0.0	0.0	86.5	5362.0	0.3	0
70	2.118	96.5	1413.8	0.0	0.0	83.9	6394.0	0.2	0
80	1.643	92.9	2794.0	0.1	0.0	79.5	8150.0	237.6	0
90	1.148	88.6	4518.0	0.5	0.0	72.9	10761.0	1323.0	0
99	0.433	70.9	11645.0	1753.0	0.0	60.6	15651.0	4218.0	0
Initial Soil Concentration:			39765.0	11975.0	716.0				

Simulation SD-11

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	97.7	466.0	0.0	0.0	78.5	4275.6	0.0	0
10	5.785	97.2	596.0	0.0	0.0	75.7	4828.7	0.0	0

20	4.818	95.7	857.0	0.0	0.0	73.9	5201.6	0.0	0
30	4.073	93.4	1315.7	0.0	0.0	84.4	3102.8	0.0	0
40	3.436	92.6	1474.0	0.0	0.0	70.7	5835.4	0.0	0
50	2.882	89.0	2191.5	0.5	0.0	79.0	4167.8	0.2	0
60	2.497	87.4	2508.3	0.3	0.0	77.5	4471.8	41.8	0
70	2.118	85.5	2891.5	6.5	0.0	74.8	5005.2	285.2	0
80	1.643	82.6	3468.9	22.9	0.0	70.9	5796.4	702.4	0
90	1.148	79.0	4182.6	68.6	0.0	66.5	6666.1	1212.1	0
99	0.433	68.3	6297.2	831.2	0.0	56.6	8631.3	2679.3	0
Initial Soil Concentration:			19891.0	5988.0	358.0				

Simulation SD-12

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	7.419	100.0	7.8	0.0	0.0	99.6	76.0	0.0	0
10	5.785	99.9	22.9	0.0	0.0	99.1	170.0	0.0	0
20	4.818	99.8	45.9	0.0	0.0	98.6	283.0	0.0	0
30	4.073	99.6	82.4	0.0	0.0	98.1	372.0	0.0	0
40	3.436	99.3	139.6	0.0	0.0	97.4	511.0	0.0	0
50	2.882	98.8	230.2	0.0	0.0	96.2	747.0	0.0	0
60	2.497	98.9	319.8	0.0	0.0	95.1	973.0	0.0	0
70	2.118	97.6	480.7	0.0	0.0	93.3	1333.4	0.0	0
80	1.643	96.5	691.8	0.0	0.0	87.6	2461.8	1.6	0
90	1.148	94.0	1194.4	0.0	0.0	84.7	3038.0	9.0	0
99	0.433	82.9	3391.8	4.8	0.0	73.5	5277.9	355.9	0

APPENDIX F

SOIL VENTING SIMULATIONS DATA SUMMARY

LOAMY SAND SOIL

Simulation LS-1

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	97	128	0	0	90	401	2	0
10	3.340	93	285	0	0	85	600	5	0
20	2.660	91	373	0	0	83	688	8	0
30	1.930	87	502	0	0	80	803	14	0
40	1.400	84	632	1	0	77	908	23	0
50	1.030	81	748	2	0	75	1,000	37	0
60	0.766	79	851	6	0	73	1,082	58	0
70	0.521	76	967	15	0	70	1,183	95	0
80	0.344	73	1,076	36	0	68	1,291	154	1
90	0.190	69	1,222	97	0	63	1,454	269	3
99	0.042	58	1,652	436	6	51	1,940	656	20
Initial Soil Concentration:			3,979	1,198	72				

Simulation LS-2

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	100	7	0	0	98	94	0	0
10	3.340	99	31	0	0	95	196	0	0
20	2.660	99	52	0	0	94	254	1	0
30	1.930	98	99	0	0	91	352	1	0
40	1.400	96	173	0	0	88	466	3	0
50	1.030	93	267	0	0	85	580	5	0
60	0.766	91	376	0	0	83	691	8	0
70	0.521	87	531	0	0	79	827	15	0
80	0.344	83	696	2	0	76	959	30	0
90	0.190	77	900	9	0	72	1,123	71	0
99	0.042	68	1,291	140	0	61	1,534	332	4
Initial Soil Concentration:			3,979	1,198	72				

Simulation LS-3

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	97	64	0	0	90	201	1	0
10	3.340	93	142	0	0	85	300	3	0
20	2.660	91	186	0	0	83	344	4	0
30	1.930	87	251	0	0	80	402	7	0

40	1.400	84	316	1	0	77	454	12	0
50	1.030	81	374	1	0	75	500	19	0
60	0.766	79	426	3	0	73	541	29	0
70	0.521	76	484	8	0	70	591	48	0
80	0.344	73	538	18	0	68	645	77	1
90	0.190	69	611	49	0	63	727	134	1
99	0.042	58	826	218	3	51	970	328	10
Initial Soil Concentration:			1,989	599	36				

Simulation LS-4

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	100	4	0	0	98	47	0	0
10	3.340	99	15	0	0	95	98	0	0
20	2.660	99	26	0	0	94	127	0	0
30	1.930	97	50	0	0	91	177	1	0
40	1.400	96	87	0	0	88	233	1	0
50	1.030	93	133	0	0	85	290	2	0
60	0.766	91	188	0	0	83	346	4	0
70	0.521	87	266	0	0	79	414	8	0
80	0.344	83	348	1	0	76	479	15	0
90	0.190	77	450	4	0	72	562	36	0
99	0.042	68	646	70	0	61	767	166	2
Initial Soil Concentration:			1,989	599	36				

Simulation LS-5

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	96	1,458	1	0	99	151	0	0
10	3.340	90	2,517	7	0	97	584	0	0
20	2.660	88	3,024	17	0	95	902	0	0
30	1.930	84	3,108	12	0	94	1,252	0	0
40	1.400	81	3,798	40	0	90	1,911	0	1
50	1.030	78	4,383	90	0	87	2,580	0	1
60	0.766	75	4,897	171	0	84	3,220	0	2
70	0.521	70	5,960	651	0	79	4,091	0	19
80	0.344	62	7,602	1,876	0	75	4,909	0	113
90	0.190	56	8,670	2,710	30	68	6,308	0	782
99	0.042	43	11,251	4,767	255	50	9,932	152	3,819
Initial Soil Concentration:			19,893	5,987	358				

Simulation LS-6

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	99	116	0	0	100	1	0	0
10	3.340	97	508	0	0	100	13	0	0
20	2.660	96	757	0	0	100	32	0	0
30	1.930	94	1,225	1	0	100	99	0	0

40	1.400	91	1,790	2	0	99	250	0	0
50	1.030	88	2,388	6	0	97	512	0	0
60	0.766	85	3,043	17	0	95	917	0	0
70	0.521	84	3,269	16	0	93	1,391	0	0
80	0.344	79	4,120	62	0	89	2,270	0	0
90	0.190	72	5,526	452	0	82	3,652	8	0
99	0.042	54	9,070	3,046	61	64	7,222	1,480	2
Initial Soil Concentration:			19,893	5,987	358				

Simulation LS-7

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	99	558	0	0	99	58	0	0
10	3.340	95	1,114	0	0	97	256	0	0
20	2.660	91	1,360	3	0	96	407	0	0
30	1.930	88	1,690	9	0	93	680	0	0
40	1.400	85	1,994	21	0	90	1,003	0	0
50	1.030	82	2,257	44	0	87	1,330	0	0
60	0.766	80	2,490	81	0	83	1,642	0	1
70	0.521	74	2,593	103	0	81	1,913	0	3
80	0.344	70	3,017	267	0	77	2,323	0	19
90	0.190	66	3,334	468	0	73	2,678	0	82
99	0.042	55	4,483	1,431	34	63	3,708	3	723
Initial Soil Concentration:			9,946	2,993	179				

Simulation LS-8

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	4-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	100	5	0	0	100	0.67	0	0
10	3.340	99	58	0	0	100	12.66	0	0
20	2.660	99	112	0	0	100	31.58	0	0
30	1.930	98	240	0	0	100	98.71	0	0
40	1.400	96	438	0	0	99	249.71	0	0
50	1.030	93	691	0	0	99	511.88	0	0
60	0.766	86	1,370	3	0	96	916.73	0	0
70	0.521	82	1,759	11	0	92	1390.80	0	0
80	0.344	78	2,140	32	0	88	2270.20	0	0
90	0.190	74	2,604	108	0	82	3651.70	2	0
99	0.042	64	3,541	619	2	71	7222.40	143	0
Initial Soil Concentration:			9,946	2,993	179				

Simulation LS-9

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	94	4,055	3	0	100	135	0	0
10	3.340	85	7,705	191	0	98	844	0	0
20	2.660	81	7,370	183	0	96	1,548	0	0

30	1.930	75	9,833	969	0	92	3,002	0	0
40	1.400	70	11,925	1,930	0	87	5,189	9	0
50	1.030	66	13,610	2,890	0	80	7,802	286	0
60	0.766	62	15,005	3,795	0	76	9,418	823	0
70	0.521	59	16,504	4,864	23	70	12,002	1,982	0
80	0.344	55	17,804	5,884	97	64	14,224	3,274	0
90	0.190	51	19,532	7,362	278	58	16,691	5,011	35
99	0.042	31	27,616	10,770	629	46	21,517	8,966	464
Initial Soil Concentration:			39,785	11,975	716				

Simulation LS-10

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	100	262	0	0	100	0	0	0
10	3.340	98	577	0	0	100	1	0	0
20	2.660	96	1,802	0	0	100	7	0	0
30	1.930	92	3,362	1	0	100	77	0	0
40	1.400	88	4,967	22	0	99	258	0	0
50	1.030	82	7,244	104	0	98	711	0	0
60	0.766	81	7,378	178	0	96	1,564	0	0
70	0.521	74	10,331	1,173	0	92	3,348	0	0
80	0.344	68	12,866	2,446	0	84	6,425	0	53
90	0.190	61	15,646	4,246	5	73	10,548	0	1,281
99	0.042	49	20,333	8,093	368	56	17,602	84	5,722
Initial Soil Concentration:			39,785	11,975	716				

Simulation LS-11

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	95	1,458	1	0	100	48	0	0
10	3.340	89	2,517	7	0	99	282	0	0
20	2.660	86	3,031	17	0	97	498	0	0
30	1.930	84	3,108	12	0	96	796	0	0
40	1.400	81	3,798	40	0	93	1,362	0	0
50	1.030	78	4,387	90	0	90	2,004	0	0
60	0.766	75	4,897	171	0	87	2,656	0	0
70	0.521	70	5,960	651	0	82	3,570	0	4
80	0.344	62	7,602	1,877	0	78	4,421	0	31
90	0.190	56	8,670	2,710	30	72	5,582	0	323
99	0.042	43	11,251	4,767	255	52	9,583	113	3,502
Initial Soil Concentration:			19,981	5,987	358				

Simulation LS-12

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	5.800	99	140	0	0	100	0	0	0
10	3.340	97	508	0	0	100	2	0	0
20	2.660	96	762	0	0	100	7	0	0

30	1.930	94	1,225	1	0	100	28	0	0
40	1.400	91	1,790	2	0	100	93	0	0
50	1.030	88	2,388	6	0	99	237	0	0
60	0.766	85	3,043	17	0	97	505	0	0
70	0.521	84	3,269	16	0	95	909	0	0
80	0.344	79	4,120	62	0	91	1,698	0	0
90	0.190	72	5,526	452	0	84	3,089	1	0
99	0.042	54	9,070	3,047	61	69	6,211	682	0
Initial Soil Concentration:			19,981	5,987	358				

APPENDIX G

SOIL VENTING SIMULATIONS DATA SUMMARY

SANDY LOAM SOIL

Simulation SL-1

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	89.2	427.7	0.1	0.0	81.4	738.7	10.2	0
10	1.08	81.6	731.3	2.2	0.0	75.2	986.8	35.3	0
20	0.655	77.4	900.4	8.7	0.0	71.7	1124.5	72.2	0
30	0.430	74.4	1019.1	23.1	0.0	69.0	1234.4	121.7	1
40	0.306	72.2	1105.3	45.3	0.0	66.7	1324.6	176.2	1
50	0.225	70.3	1180.9	75.9	0.0	64.6	1409.8	236.2	2
60	0.156	68.0	1273.6	129.6	0.2	61.9	1517.0	319.8	4
70	0.114	65.9	1357.9	187.9	0.6	59.4	1613.7	399.4	6
80	0.068	62.1	1509.0	310.6	2.1	55.2	1781.6	538.9	12
90	0.036	57.0	1709.9	488.9	7.7	49.6	2003.6	705.1	23
99	0.008	43.6	2243.5	870.6	38.8	32.2	2696.8	998.7	53
Initial Soil Concentration:			3979.0	1198.0	72.0				

Simulation SL-2

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	98.2	69.8	0.0	0.0	92.6	295.3	1.0	0
10	1.08	93.7	251.2	0.0	0.0	85.9	562.7	4.3	0
20	0.655	89.0	438.2	0.2	0.0	81.2	747.9	10.6	0
30	0.430	84.7	608.9	0.8	0.0	77.6	890.2	21.4	0
40	0.306	81.4	739.9	2.3	0.0	75.0	993.6	36.5	0
50	0.225	78.7	846.7	5.6	0.0	72.9	1079.2	57.0	0
60	0.156	75.9	957.9	13.9	0.0	70.4	1175.8	93.3	0
70	0.114	73.8	1042.2	28.2	0.0	68.4	1257.7	134.8	1
80	0.068	70.6	1170.6	71.6	0.0	64.9	1397.9	227.5	2
90	0.036	66.5	1334.3	171.3	0.4	60.1	1586.8	376.8	6
99	0.008	54.9	1795.3	565.4	11.7	47.1	2104.4	769.6	29
Initial Soil Concentration:			3979.0	1198.0	72.0				

Simulation SL-3

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	89.2	213.9	0.1	0.0	81.4	369.3	5.0	0
10	1.08	81.6	365.6	1.0	0.0	75.2	493.4	17.6	0
20	0.655	77.4	450.2	4.3	0.0	71.7	562.2	36.1	0
30	0.430	74.4	509.6	11.6	0.0	69.0	617.2	60.9	0

40	0.306	72.2	552.7	22.7	0.0	66.7	662.3	88.1	1
50	0.225	71.1	575.1	31.2	0.0	65.4	687.3	105.3	1
60	0.156	68.0	636.8	64.6	0.1	61.9	758.5	160.0	2
70	0.114	65.9	679.0	94.3	0.3	59.4	806.8	199.8	3
80	0.068	62.1	754.5	155.4	1.1	55.2	890.8	269.3	6
90	0.036	57.0	854.9	244.4	3.8	49.6	1001.8	352.8	12
99	0.008	43.6	1121.7	435.3	19.4	32.2	1348.4	499.6	26
Initial Soil Concentration:			1989.0	599.0	36.0				

Simulation SL-4

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	1-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	98.2	34.9	0.0	0.0	92.6	147.7	0.6	0
10	1.08	93.7	125.6	0.0	0.0	85.9	281.4	2.2	0
20	0.655	89.0	219.1	0.1	0.0	81.2	374.0	5.3	0
30	0.430	84.7	304.5	0.4	0.0	77.6	445.1	10.7	0
40	0.306	81.4	369.9	1.1	0.0	75.0	496.8	18.3	0
50	0.225	78.7	423.3	2.8	0.0	72.9	539.6	28.6	0
60	0.156	75.9	479.0	7.0	0.0	70.4	587.9	46.4	0
70	0.114	73.8	521.1	13.9	0.0	68.4	628.8	67.4	0
80	0.068	70.6	585.3	35.8	0.0	64.9	698.9	113.7	1
90	0.036	66.5	667.1	85.4	0.2	60.1	793.4	188.6	3
99	0.008	54.9	897.6	282.5	5.9	47.1	1052.2	384.6	14
Initial Soil Concentration:			1989.0	599.0	36.0				

Simulation SL-5

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	84.8	3018.2	14.2	0.0	96.9	607.3	0.0	0
10	1.08	78.4	4298.4	80.4	0.0	90.5	1898.8	0.2	0
20	0.655	72.2	5529.5	454.5	0.0	84.5	3091.3	1.3	0
30	0.430	68.3	6300.7	833.7	0.0	80.2	3937.3	8.3	0
40	0.306	60.6	7838.5	2053.5	2.2	76.8	4611.0	46.0	0
50	0.225	57.8	8399.0	2490.0	15.9	73.9	5186.2	160.2	0
60	0.156	54.9	8968.3	2960.3	51.9	69.4	6094.0	618.0	0
70	0.114	52.5	9439.6	3372.6	97.2	65.2	6923.4	1205.4	1
80	0.068	48.4	10271.0	4135.3	186.5	55.7	8822.3	2838.3	42
90	0.036	41.1	11723.0	4958.0	272.1	50.5	9843.2	3739.0	140
99	0.008	14.0	17117.0	5779.0	342.8	29.5	14020.0	5436.0	315
Initial Soil Concentration:			19893.0	5987.0	358.0				

Simulation SL-6

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	95.3	944.7	0.0	0.0	99.9	12.6	0.0	0
10	1.08	88.5	2295.0	5.0	0.0	99.0	208.5	0.1	0
20	0.655	86.3	2729.9	2.9	0.0	97.1	571.6	0.0	0
30	0.430	81.5	3678.9	32.9	0.0	93.7	1250.0	0.0	0

40	0.306	78.2	4341.3	85.3	0.0	90.2	1949.3	0.3	0
50	0.225	75.5	4875.3	167.3	0.0	86.8	2626.0	0.0	0
60	0.156	70.4	5897.3	620.3	0.0	82.4	3502.5	2.5	0
70	0.114	67.6	6452.8	922.8	0.0	79.4	4096.7	11.7	0
80	0.068	58.2	8319.0	2426.0	12.8	74.3	5122.2	144.2	0
90	0.036	53.2	9300.3	3248.3	82.9	66.0	6769.8	1099.8	1
99	0.008	36.2	12690.0	5208.0	295.4	48.4	10274.0	4124.3	185
Initial Soil Concentration:			19893.0	5987.0	358.0				

Simulation SL-7

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	88.1	1188.1	0.1	0.0	97.6	240.2	0.0	0
10	1.08	80.7	1921.2	0.2	0.0	91.3	864.9	0.0	0
20	0.655	76.8	2305.0	102.0	0.0	86.7	1320.6	0.6	0
30	0.430	72.1	2779.0	147.0	0.0	81.0	1893.6	1.6	0
40	0.306	70.0	2982.1	255.1	0.0	78.3	2159.1	7.1	0
50	0.225	67.7	3211.2	387.2	0.0	75.9	2392.2	22.2	0
60	0.156	64.9	3489.9	580.9	1.4	73.5	2637.9	62.9	0
70	0.114	62.5	3727.9	766.9	4.3	71.5	2834.4	126.4	0
80	0.068	58.5	4125.0	1107.0	15.0	68.2	3164.2	303.2	0
90	0.036	53.3	4644.8	1574.7	43.8	63.6	3623.4	649.4	2
99	0.008	24.9	7467.0	2785.0	161.4	49.1	5061.8	1923.3	72
Initial Soil Concentration:			9946.0	2993.0	179.0				

Simulation SL-8

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	98.4	158.9	0.0	0.0	100.0	4.4	0.0	0
10	1.08	93.5	648.9	0.0	0.0	99.1	88.1	0.0	0
20	0.655	86.6	1331.1	5.1	0.0	96.8	319.8	0.1	0
30	0.430	82.5	1741.0	19.0	0.0	93.4	659.1	0.0	0
40	0.306	78.5	2138.7	42.7	0.0	89.9	1006.0	0.0	0
50	0.225	75.1	2480.3	79.3	0.0	86.5	1339.2	0.2	0
60	0.156	72.4	2743.1	149.1	0.0	82.7	1720.8	0.8	0
70	0.114	70.1	2978.9	250.9	0.0	79.7	2018.7	3.7	0
80	0.068	67.6	3225.8	386.8	0.3	76.0	2385.1	20.1	0
90	0.036	63.2	3662.3	714.3	3.2	72.0	2780.8	105.8	0
99	0.008	51.0	4869.6	1757.8	59.0	61.5	3830.6	826.6	4
Initial Soil Concentration:			9946.0	2993.0	179.0				

Simulation SL-9

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	78.7	8471.2	484.2	0.0	94.9	2045.0	0.0	0
10	1.08	66.4	13374.0	2744.0	0.0	81.3	7447.9	212.9	0
20	0.655	60.7	15651.0	4241.0	5.6	73.5	10556.0	1285.0	0

30	0.430	56.9	17136.0	5346.0	51.2	67.1	13084.0	2574.0	0
40	0.306	54.4	18140.0	6160.0	127.3	62.9	14765.0	3635.0	2
50	0.225	52.1	19048.0	6938.0	222.3	59.6	16064.0	4544.0	17
60	0.156	49.4	20136.0	7916.0	344.3	56.4	17366.0	5536.0	68
70	0.114	46.9	21136.0	8777.4	441.6	53.9	18351.0	6341.0	148
80	0.068	40.1	23816.0	9999.0	562.5	50.0	19901.0	7696.1	317
90	0.036	27.4	28872.0	10970.0	643.3	44.1	22237.0	9375.1	503
99	0.008	7.3	36882.0	11762.0	701.9	17.0	33028.0	11433.0	679
Initial Soil Concentration:			39785.0	11975.0	716.0				

Simulation SL-10

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	94.2	2321.0	0.0	0.0	99.9	30.9	0.0	0
10	1.08	82.6	6905.0	51.0	0.0	98.4	623.8	0.0	0
20	0.655	78.2	8669.3	548.3	0.0	94.6	2144.6	0.4	0
30	0.430	70.9	11578.0	1753.0	0.0	88.5	4590.5	2.5	0
40	0.306	66.1	13493.0	2823.0	0.0	82.5	6970.8	161.8	0
50	0.225	62.4	14947.0	3757.0	0.0	76.6	9318.2	787.2	0
60	0.156	58.8	16391.0	4781.0	20.1	70.3	11807.0	1878.0	0
70	0.114	56.2	17407.0	5557.0	67.9	65.9	13556.0	2856.0	0
80	0.068	52.5	18890.0	6790.0	204.7	60.1	15879.0	4409.0	13
90	0.036	47.6	20841.0	8541.7	416.5	54.5	18089.0	6119.0	124
99	0.008	22.3	30911.0	11217.0	662.4	40.2	23798.0	9966.0	559
Initial Soil Concentration:			39785.0	11975.0	716.0				

Simulation SL-11

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	84.8	3018.1	14.1	0.0	96.9	607.3	0.0	0
10	1.08	78.4	4298.3	80.3	0.0	90.5	1898.8	0.2	0
20	0.655	72.2	5529.3	454.3	0.0	84.5	3091.2	1.2	0
30	0.430	68.3	6300.5	834.5	0.0	80.2	3937.2	8.2	0
40	0.306	60.6	7838.2	2054.2	2.2	76.8	4610.8	46.8	0
50	0.225	57.8	8398.7	2490.7	15.9	73.9	5186.1	160.1	0
60	0.156	54.9	8968.0	2960.0	51.9	69.4	6093.9	617.9	0
70	0.114	52.5	9439.3	3372.3	97.2	65.2	6923.2	1205.2	1
80	0.068	48.4	10270.0	4135.3	186.5	55.7	8822.0	2838.0	42
90	0.036	41.1	11722.0	4957.0	272.1	50.5	9842.9	3739.7	140
99	0.008	14.0	17117.0	5780.0	342.7	29.5	14020.0	5437.0	315
Initial Soil Concentration:			19981.0	5987.0	358.0				

Simulation SL-12

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	2.32	95.3	944.7	0.0	0.0	99.9	12.6	0.0	0
10	1.08	88.5	2295.0	5.0	0.0	99.0	208.5	0.0	0
20	0.655	86.3	2729.8	2.8	0.0	97.1	571.6	0.0	0

30	0.430	81.5	3678.8	32.8	0.0	93.7	1250.0	0.0	0
40	0.306	78.2	4341.2	85.2	0.0	90.2	1949.3	0.3	0
50	0.225	75.5	4875.2	167.2	0.0	86.8	2626.0	0.0	0
60	0.156	70.4	5897.1	620.1	0.0	82.4	3502.4	3.4	0
70	0.114	67.6	6452.6	922.6	0.0	79.4	4096.7	11.7	0
80	0.068	58.2	8318.7	2425.7	12.8	74.3	5122.1	145.1	0
90	0.036	53.2	9300.0	3248.0	82.9	66.0	6769.7	1099.7	1
99	0.008	36.2	12690.0	5208.0	295.4	48.4	10273.0	4123.3	185
Initial Soil Concentration:			19981.0	5987.0	358.0				

APPENDIX H

SOIL VENTING SIMULATIONS DATA SUMMARY

LOAM SOIL

Simulation LM-1

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	77.3	1055.6	27.5	0.1	86.8	613.0	0.2	0.0
10	0.299	72.1	1296.0	80.6	0.4	79.9	935.0	3.1	0.0
20	0.149	67.4	1514.2	187.7	1.5	74.6	1178.7	21.7	0.0
30	0.081	62.9	1723.5	338.6	4.0	70.8	1359.0	77.0	0.0
40	0.049	59.1	1903.1	483.9	8.2	67.6	1505.0	162.0	0.3
50	0.033	55.5	2066.4	619.7	14.0	64.6	1645.2	266.2	1.0
60	0.021	51.6	2251.5	763.8	22.7	61.0	1813.5	409.2	3.2
70	0.013	47.1	2460.8	903.5	34.0	57.0	2000.9	576.9	8.8
80	0.008	41.9	2699.7	1024.7	45.9	52.9	2187.7	745.0	18.6
90	0.004	33.1	3109.0	1159.6	60.6	47.0	2464.6	949.4	37.3
99	0.00004	6.8	4330.4	1364.4	80.8	15.2	3939.5	1317.5	76.7
Initial Soil Concentration:			4648.0	1399.0	84.0				

Simulation LM-2

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	88.5	536.6	3.2	0.0	97.4	119.0	0.0	0.0
10	0.299	81.8	844.9	11.5	0.0	92.2	363.1	-0.1	0.0
20	0.149	76.0	1115.0	35.9	0.1	85.1	692.2	0.5	0.0
30	0.081	71.6	1318.3	88.9	0.5	79.3	963.2	3.9	0.0
40	0.049	68.4	1469.4	161.2	1.1	75.6	1134.6	15.6	0.0
50	0.033	66.7	1552.0	198.0	1.0	73.0	1251.0	29.0	0.0
60	0.021	63.0	1704.0	317.0	1.9	70.0	1374.0	76.0	0.0
70	0.013	59.0	1886.0	474.0	5.4	67.0	1518.0	164.0	0.0
80	0.008	55.0	2075.0	642.0	12.7	64.0	1688.0	298.0	0.7
90	0.004	48.5	2390.0	811.0	32.0	57.0	2001.0	578.0	7.5
99	0.00004	19.2	3756.0	1291.0	74.3	34.0	3048.0	1170.0	62.2
Initial Soil Concentration:			4648.0	1399.0	84.0				

Simulation LM-3

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	77.3	527.8	14.0	0.1	86.8	306.5	0.1	0.0
10	0.299	72.1	648.0	40.3	0.2	79.9	467.5	1.5	0.0
20	0.149	67.4	757.1	93.9	0.7	74.6	589.3	10.9	0.0

30	0.081	62.9	861.7	169.0	2.0	70.8	679.5	38.5	0.0
40	0.049	59.1	951.5	242.1	4.1	67.6	752.5	80.8	0.1
50	0.033	55.5	1033.2	309.7	7.0	64.6	822.6	133.3	0.5
60	0.021	51.6	1125.7	382.1	11.4	61.0	906.8	204.5	1.6
70	0.013	47.1	1230.4	452.0	17.0	57.0	1000.4	288.7	4.4
80	0.008	44.2	1296.0	504.0	21.9	53.3	1084.0	366.0	8.4
90	0.004	33.7	1542.0	586.0	30.8	46.8	1236.0	484.0	19.6
99	0.00004	6.9	2162.0	682.0	40.4	15.4	1964.0	658.0	38.3
Initial Soil Concentration:			2324.0	700.0	41.0				

Simulation LM-4

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	88.5	268.3	0.0	0.0	97.4	59.5	0.0	0.0
10	0.299	81.8	422.4	0.0	0.0	92.2	181.5	0.0	0.0
20	0.149	76.0	557.5	0.0	0.1	85.1	346.1	0.2	0.0
30	0.081	71.6	659.1	0.0	0.2	79.3	481.6	2.0	0.0
40	0.049	68.4	734.7	0.1	0.6	75.6	567.3	7.7	0.0
50	0.033	65.5	802.5	0.2	1.2	72.9	630.3	20.1	0.0
60	0.021	62.1	881.8	0.5	2.4	70.1	695.7	46.4	0.0
70	0.013	58.2	972.5	1.2	4.8	66.9	770.0	93.0	0.2
80	0.008	54.0	1069.2	2.8	8.6	63.2	854.9	159.9	0.8
90	0.004	47.6	1216.7	8.1	16.3	57.5	988.7	278.0	3.9
99	0.00004	18.4	1896.9	57.3	37.2	33.5	1545.2	586.6	31.2
Initial Soil Concentration:			2324.0	700.0	41.0				

Simulation LM-5

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	65.8	8683.1	1732.1	0.0	81.5	4915.2	194.8	0.0
10	0.299	58.4	10571.0	3089.0	0.0	70.5	7487.2	1032.2	0.0
20	0.149	53.3	11863.0	4144.0	106.4	61.7	9725.1	2456.1	1.9
30	0.081	48.7	13027.0	5206.0	228.9	56.2	11141.0	3542.0	44.9
40	0.049	45.3	13898.0	6029.0	316.2	52.2	12137.0	4395.0	132.3
50	0.033	38.4	15645.0	6591.0	370.4	48.9	12978.0	5159.1	221.3
60	0.021	28.9	18069.0	6996.0	406.1	44.8	14033.0	5949.9	307.3
70	0.013	19.7	20395.0	7258.0	427.6	37.4	15905.0	6605.0	371.2
80	0.008	12.9	22138.0	7414.0	439.8	27.7	18371.0	7026.0	408.5
90	0.004	6.7	23705.0	7533.0	448.9	15.7	21420.0	7352.0	435.0
99	0.00004	0.7	25233.0	7636.0	456.6	1.7	24971.0	7620.0	455.3
Initial Soil Concentration:			25410.0	7648.0	457.0				

Simulation LM-6

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	83.6	4164.0	0.0	0.0	96.3	928.7	0.0	0.0
10	0.299	72.8	6906.8	738.8	0.0	91.5	3806.0	0.0	0.0
20	0.149	63.8	9195.2	2082.2	0.0	78.8	5381.5	0.0	0.0
30	0.081	57.8	10722.0	3206.0	4.1	69.5	7752.9	0.0	0.0

40	0.049	54.4	11594.0	3910.0	78.9	63.3	9329.1	0.0	0.0
50	0.033	51.2	12407.0	4633.0	164.1	59.0	10419.0	0.0	12.5
60	0.021	48.0	13218.0	5385.0	248.5	55.3	11359.0	23.9	60.3
70	0.013	43.9	14254.0	6193.9	332.5	51.4	12360.0	143.3	155.7
80	0.008	34.7	16581.0	6773.0	386.7	47.5	13350.0	350.4	257.6
90	0.004	20.8	20128.0	7231.0	425.5	38.5	15616.0	641.1	364.7
99	0.00004	2.4	24806.0	7609.0	454.5	5.8	23930.0	915.3	450.1
Initial Soil Concentration:			25410.0	7648.0	457.0				

Simulation LM-7

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	76.0	3043.3	0.3	0.0	85.7	1814.9	0.0	0.0
10	0.299	66.1	4312.7	746.7	0.0	78.2	2765.7	0.0	0.0
20	0.149	59.0	5204.2	1431.2	0.0	72.8	3452.2	0.0	0.0
30	0.081	54.1	5836.8	1970.8	38.6	68.4	4008.6	0.0	0.4
40	0.049	50.3	6320.1	2415.1	86.5	64.9	4462.3	0.0	2.7
50	0.033	47.1	6715.7	2788.7	127.1	61.6	4883.5	0.6	8.7
60	0.021	42.5	7306.5	3170.5	167.8	57.7	5372.2	3.1	23.7
70	0.013	33.2	8484.4	3433.4	193.9	51.8	6127.6	29.1	69.9
80	0.008	23.3	9739.8	3592.8	208.8	40.7	7530.8	277.6	170.6
90	0.004	12.8	11075.0	3713.0	219.4	27.5	9209.0	381.0	202.9
99	0.00004	1.4	12529.0	3813.0	227.8	3.4	12271.0	462.3	226.5
Initial Soil Concentration:			12705.0	3824.0	229.0				

Simulation LM-8

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	88.0	1377.0	0.0	0.0	97.0	304.0	0.0	0.0
10	0.299	80.0	2260.0	0.0	0.0	91.0	985.0	0.0	0.0
20	0.149	69.0	3555.0	700.0	0.0	83.0	1981.0	0.0	0.0
30	0.081	64.1	4557.0	875.0	0.0	77.1	2912.9	39.9	0.0
40	0.049	60.3	5044.9	1302.9	0.0	73.8	3322.7	119.7	0.0
50	0.033	56.7	5498.2	1676.2	9.8	70.9	3701.5	255.5	0.0
60	0.021	53.2	5947.3	2070.3	49.4	67.6	4110.6	482.6	0.7
70	0.013	49.4	6424.4	2513.4	97.1	64.0	4568.9	814.9	3.7
80	0.008	46.0	6864.4	2931.4	142.2	60.1	5070.4	1235.4	13.2
90	0.004	34.5	8324.8	3406.9	191.3	52.3	6062.3	2134.4	65.3
99	0.00004	4.7	12111.0	3787.0	225.6	11.2	11286.0	3729.0	220.8
Initial Soil Concentration:			12705.0	3824.0	229.0				

Simulation LM-9

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	60.0	18615.0	12.1	5225.0	72.3	12878.0	1818.0	0.0
10	0.299	54.2	21299.0	7299.0	159.8	62.6	17399.0	4379.0	3.8
20	0.149	48.9	23752.0	9462.0	423.4	55.9	20503.0	6653.0	95.7
30	0.081	42.8	26598.0	11309.7	618.2	51.2	22694.0	8504.0	306.0

40	0.049	34.1	30640.0	12356.0	712.6	47.4	24469.0	10039.5	487.5
50	0.033	25.6	34593.0	12944.0	760.2	42.8	26592.0	11258.0	613.2
60	0.021	17.7	38255.0	13345.0	790.4	35.0	30235.0	12263.0	705.0
70	0.013	11.5	41129.0	13599.0	809.1	25.3	34729.0	12958.0	761.3
80	0.008	7.0	43217.0	13757.0	820.7	16.4	38862.0	13392.0	794.6
90	0.004	3.4	44920.0	13880.0	829.4	8.2	42692.0	13722.0	817.9
99	0.00004	0.4	46305.0	13985.0	835.9	0.9	46041.0	13961.0	834.7
Initial Soil Concentration:			46482.0	13992.0	837.0				

Simulation LM-10

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	76.9	10749.0	939.0	0.0	94.5	2554.8	-0.2	0.0
10	0.299	65.7	15924.0	3434.0	0.0	82.4	8181.7	245.7	0.0
20	0.149	58.3	19370.0	5780.0	31.8	69.5	14164.0	2444.0	0.0
30	0.081	53.7	21538.0	7498.0	183.1	61.8	17757.0	4627.0	6.2
40	0.049	50.0	23232.0	8992.0	366.8	57.1	19933.0	6203.0	61.4
50	0.033	46.7	24768.0	10320.9	518.8	53.8	21489.0	7459.0	178.6
60	0.021	41.1	27389.0	11582.0	644.5	50.3	23089.0	8856.1	349.5
70	0.013	31.9	31671.0	12529.0	727.3	46.4	24930.0	10376.9	523.9
80	0.008	21.6	36453.0	13154.0	776.7	39.4	28169.0	11782.0	662.7
90	0.004	11.0	41359.0	13619.0	810.4	24.4	35143.0	13010.0	765.1
99	0.00004	1.3	45877.0	13957.0	833.9	3.2	44985.0	13885.0	829.7
Initial Soil Concentration:			46482.0	13992.0	837.0				

Simulation LM-11

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	68.7	7275.6	1155.6	0.0	83.3	3885.1	5.1	0.0
10	0.299	60.2	9238.3	2485.3	4.2	73.9	6060.9	426.9	0.0
20	0.149	54.4	10599.0	3576.0	71.6	63.1	8576.8	2001.8	1.1
30	0.081	49.5	11741.0	4600.0	187.7	57.0	9992.6	3072.6	30.4
40	0.049	45.3	12719.0	5390.0	274.5	52.9	10943.0	3878.0	104.0
50	0.033	39.3	14098.0	5937.4	328.9	49.6	11724.0	4581.6	185.0
60	0.021	30.4	16170.0	6342.0	365.9	45.6	12654.0	5318.5	266.7
70	0.013	21.1	18328.0	6606.0	388.1	38.9	14205.0	5952.0	330.3
80	0.008	13.4	20121.0	6770.0	401.3	28.6	16599.0	6401.0	370.9
90	0.004	6.6	21708.0	6893.0	410.7	15.5	19649.0	6731.0	398.1
99	0.00004	0.8	23064.0	6984.0	417.5	1.9	22802.0	6968.0	416.2
Initial Soil Concentration:			23241.0	6996.0	418.0				

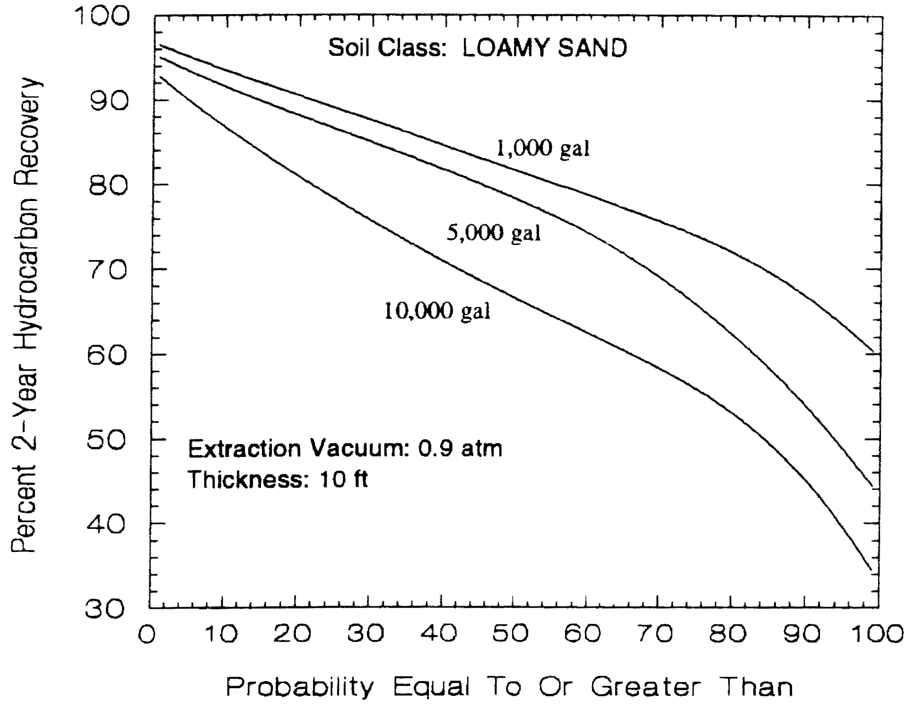
Simulation LM-12

% Probability of Occurrence	Air Permeability	2-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)	5-YEAR Cumulative Change in Hydrocarbon (%)	Total Hydrocarbon Mass Per Soil Mass (mg/kg)	MTBE, N-Hexane, & BETX (mg/kg)	Benzene Alone (mg/kg)
1	0.614	86.6	3107.2	7.2	0.0	97.5	571.1	0.0	0.0
10	0.299	72.9	6295.8	565.8	0.0	89.8	2362.3	0.3	0.0
20	0.149	66.3	7832.3	1501.3	0.0	81.0	4426.2	19.2	0.0

30	0.081	59.6	9393.6	2602.6	6.8	71.5	6616.7	786.7	0.0
40	0.049	55.5	10342.0	3358.0	50.7	64.8	8177.4	1727.4	0.0
50	0.033	52.3	11082.0	3999.0	118.0	60.2	9243.6	2488.6	6.7
60	0.021	48.6	11938.0	4784.0	208.4	56.0	10217.0	3256.0	43.4
70	0.013	44.0	13017.0	5550.8	290.9	52.0	11149.0	4061.0	124.7
80	0.008	35.2	15053.0	6154.0	349.2	47.8	12141.0	4944.1	226.2
90	0.004	20.4	18507.0	6624.0	389.6	38.1	14392.0	6000.0	334.9
99	0.00004	2.6	22638.0	6956.0	415.4	6.3	21767.0	6897.0	411.0
Initial Soil Concentration:			23241.0	6996.0	418.0				

APPENDIX I

LOAMY SAND SOIL PARAMETER PROBABILITY PLOTS



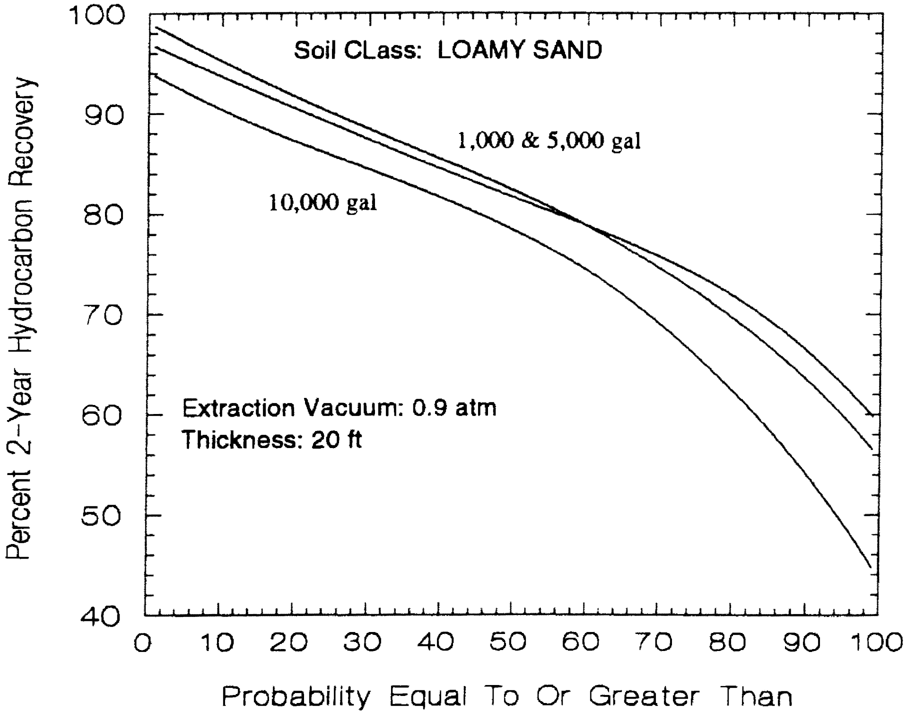
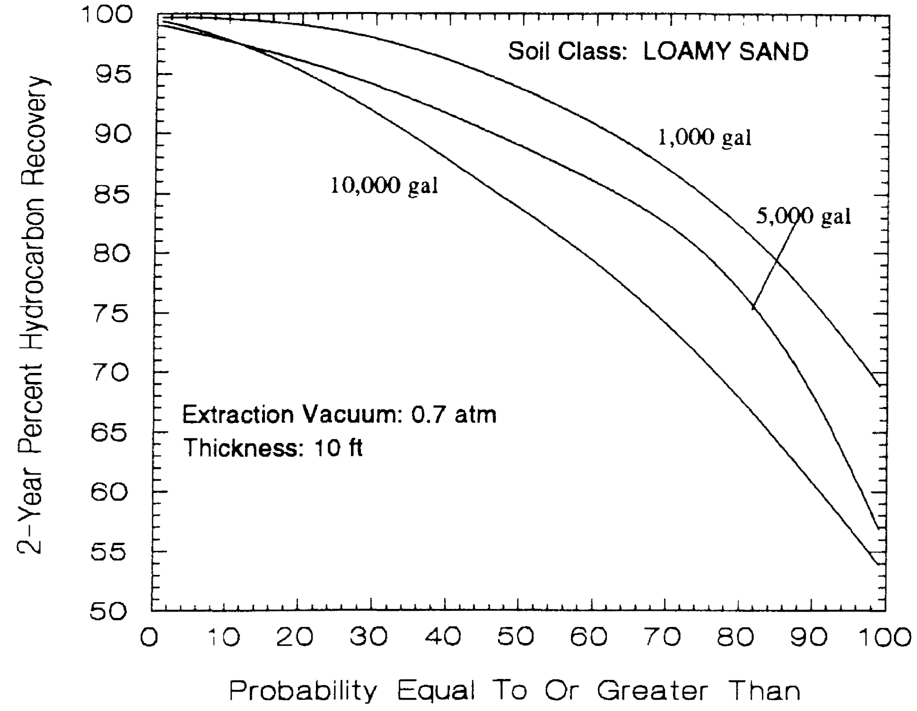


Figure 27. LOAMY SAND SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.9 atm vacuum at 10 and 20 foot thickness.



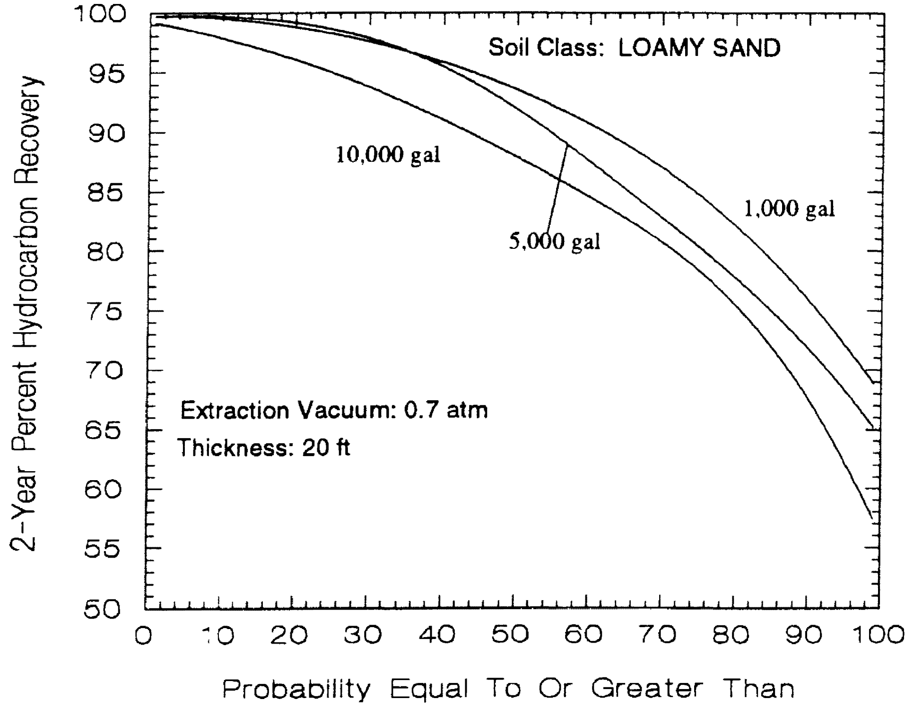
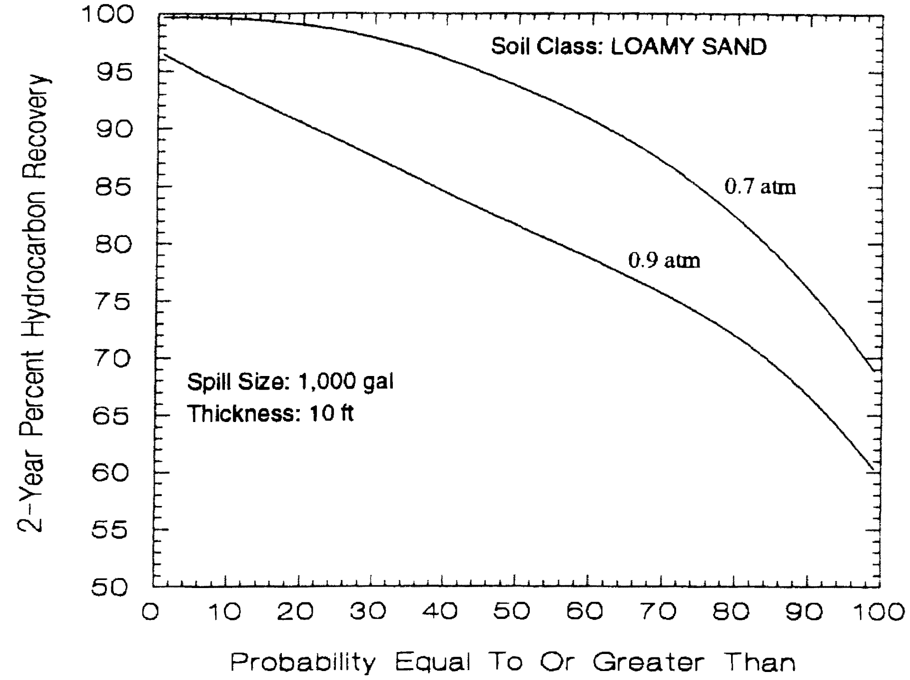


Figure 28. LOAMY SAND SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.7 atm vacuum at 10 and 20 foot thickness.



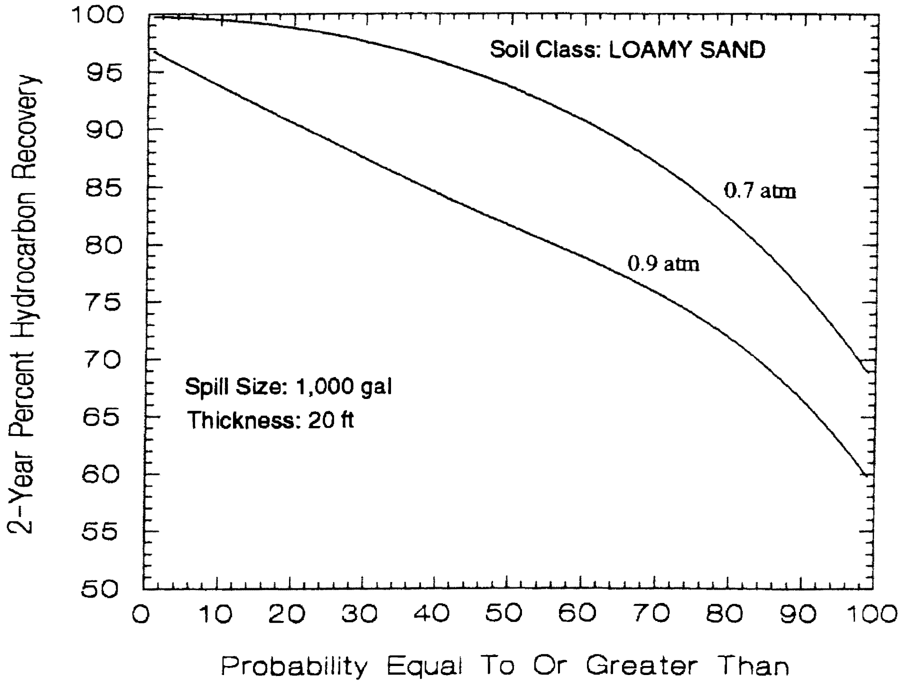


Figure 29. LOAMY SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 1,000 gal composite gasoline spill at 10 and 20 ft thickness.

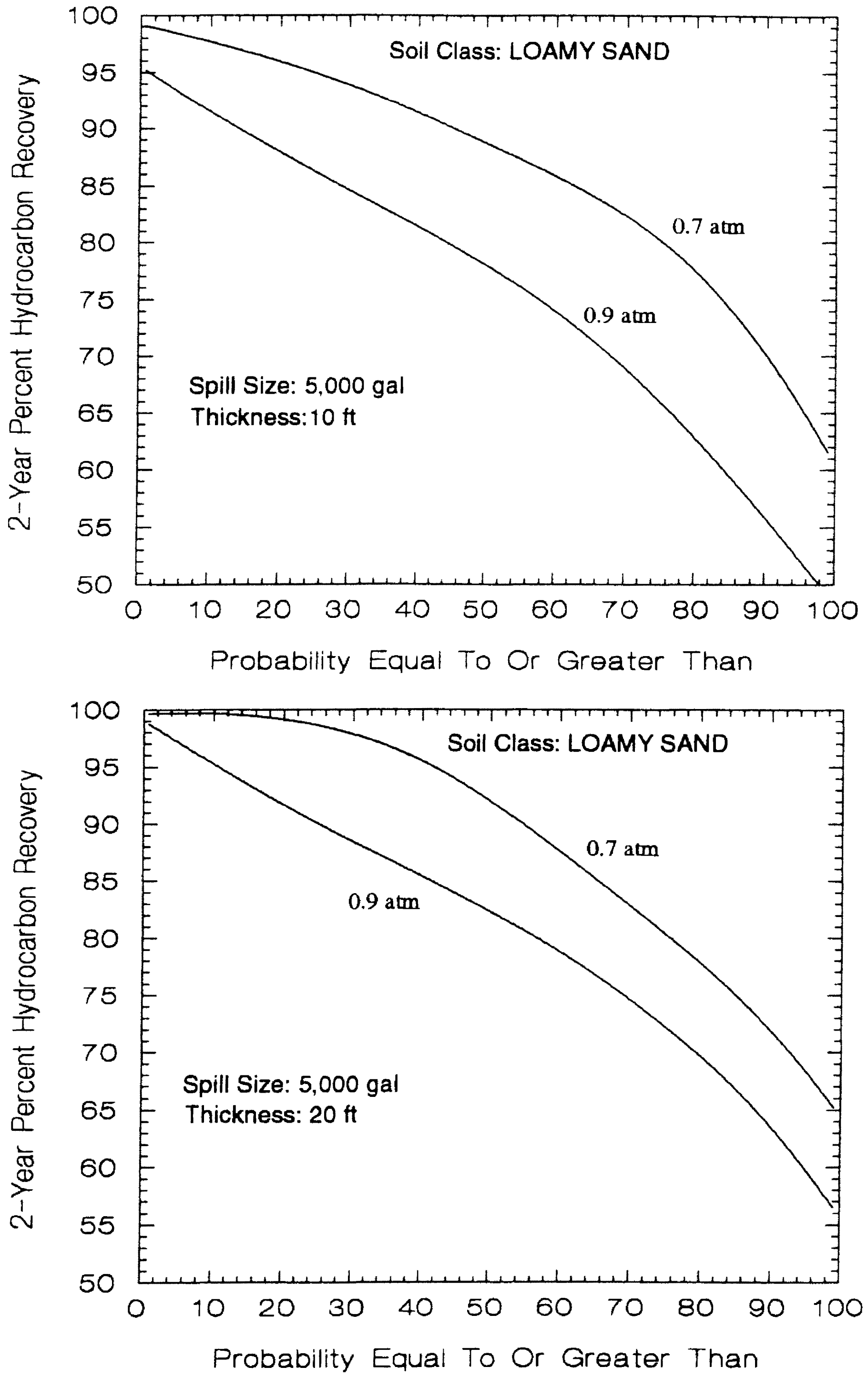
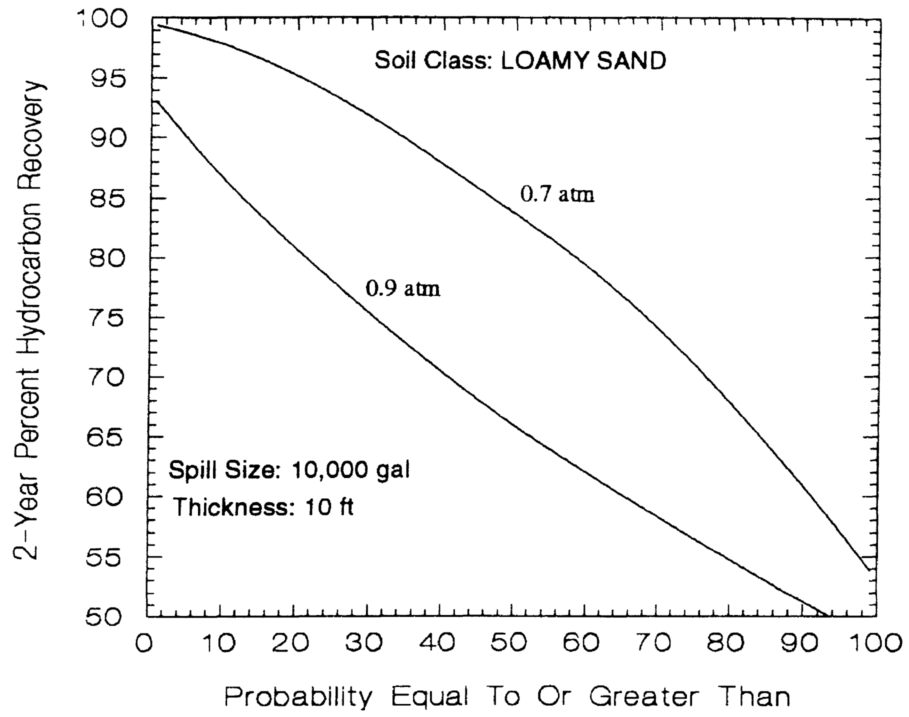


Figure 30. LOAMY SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 5,000 gal composite gasoline spill at 10 and 20 ft thickness.



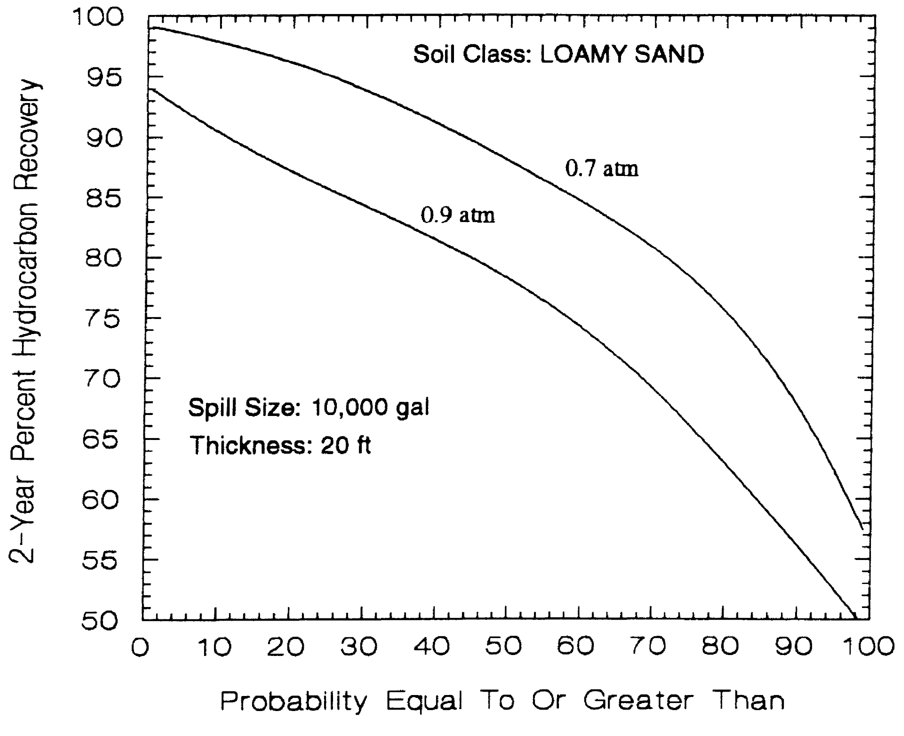
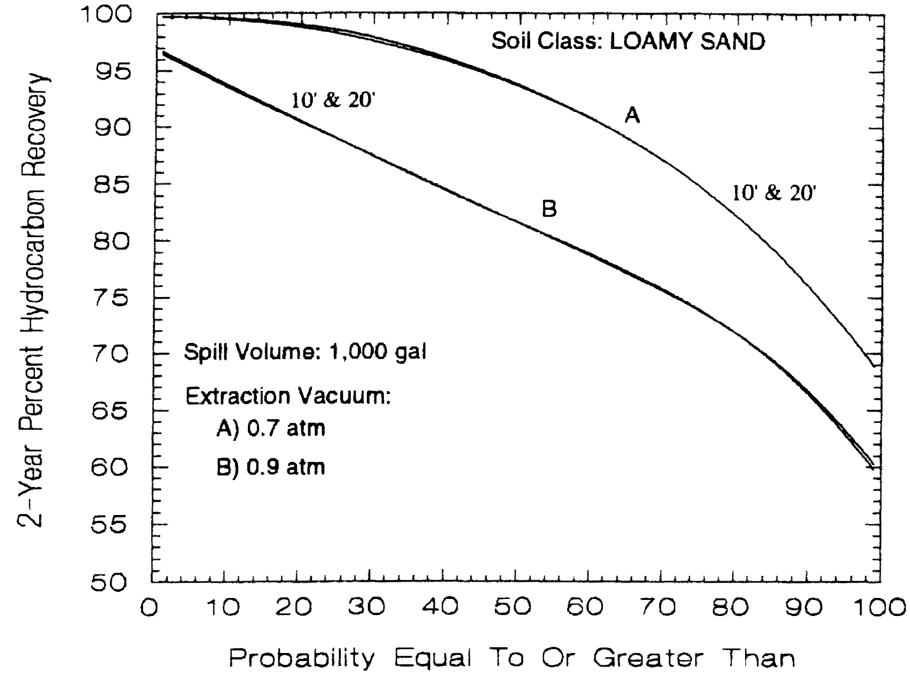


Figure 31. LOAMY SAND SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 10,000 gal composite gasoline spill at 10 and 20 ft thickness.



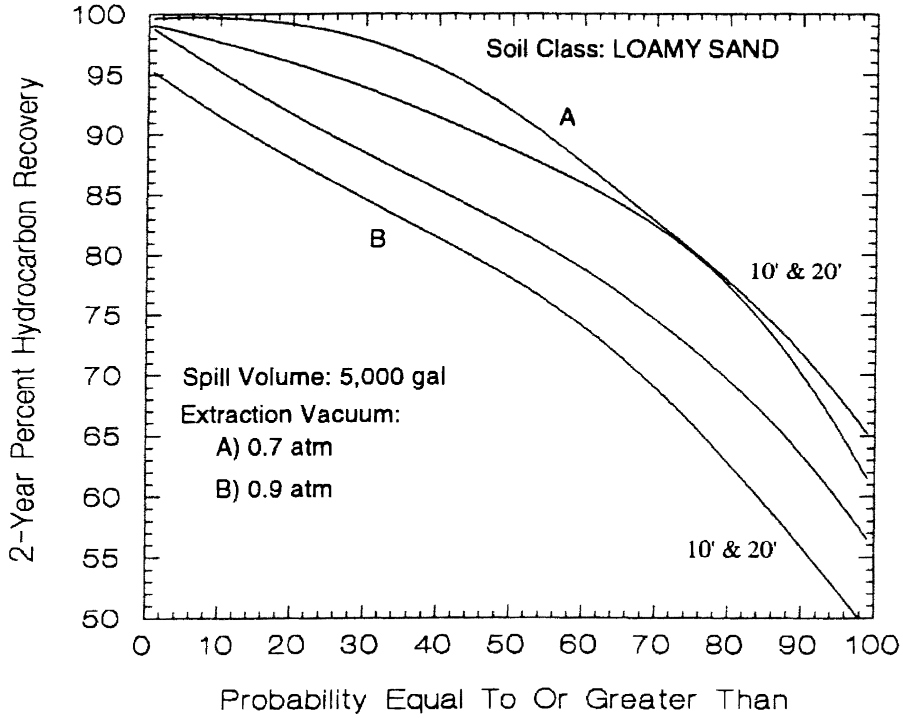


Figure 32. LOAMY SAND SOIL control variable analysis plots for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery using 0.7 and 0.9 atm vaccum at two spill sizes.

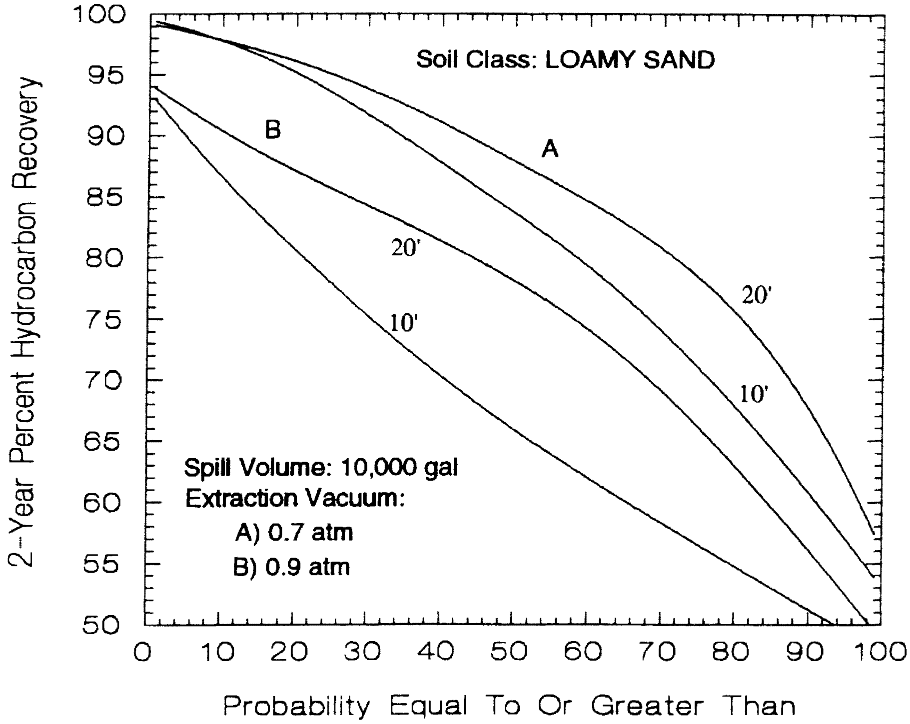
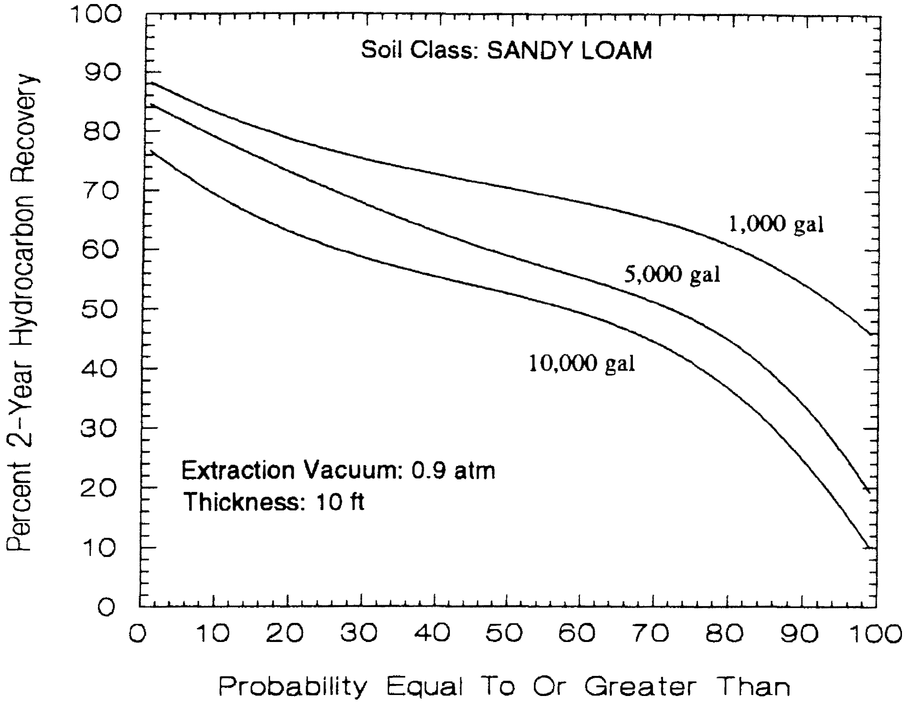


Figure 33. LOAMY SAND SOIL control variable analysis plots for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery using 0.7 and 0.9 atm vaccum at 10,000 gallon spill size.

APPENDIX J

SANDY LOAM PARAMETER PROBABILITY PLOTS



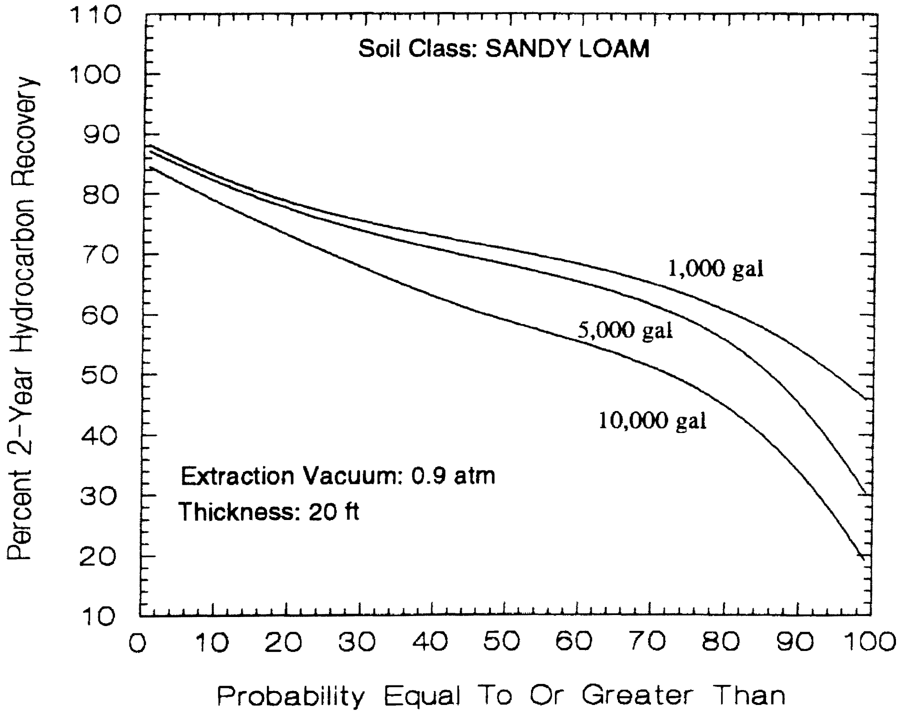
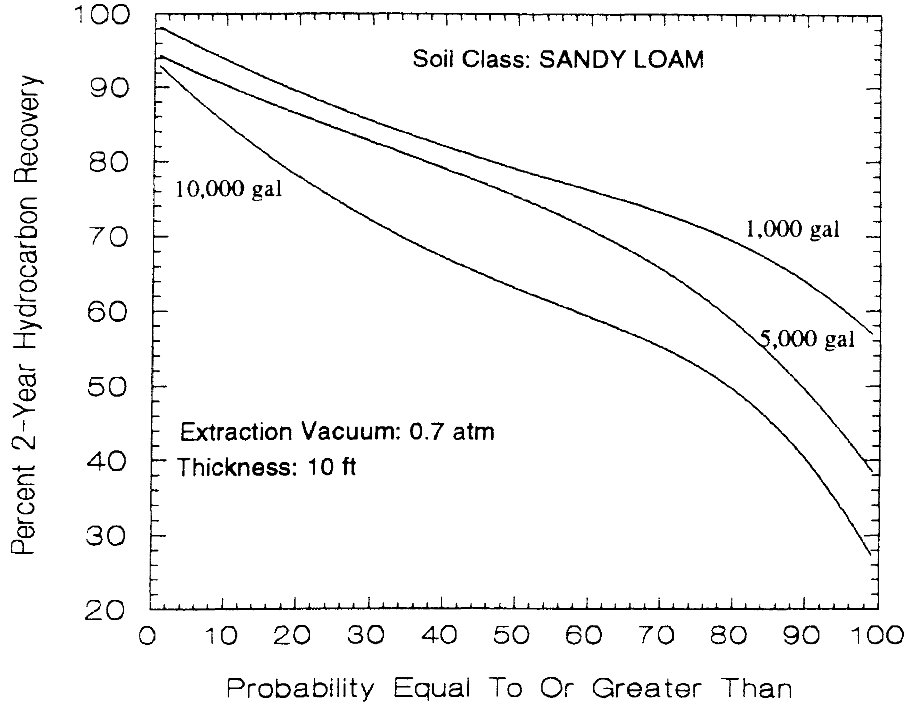


Figure 34. SANDY LOAM SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.9 atm vacuum at 10 and 20 foot thickness.



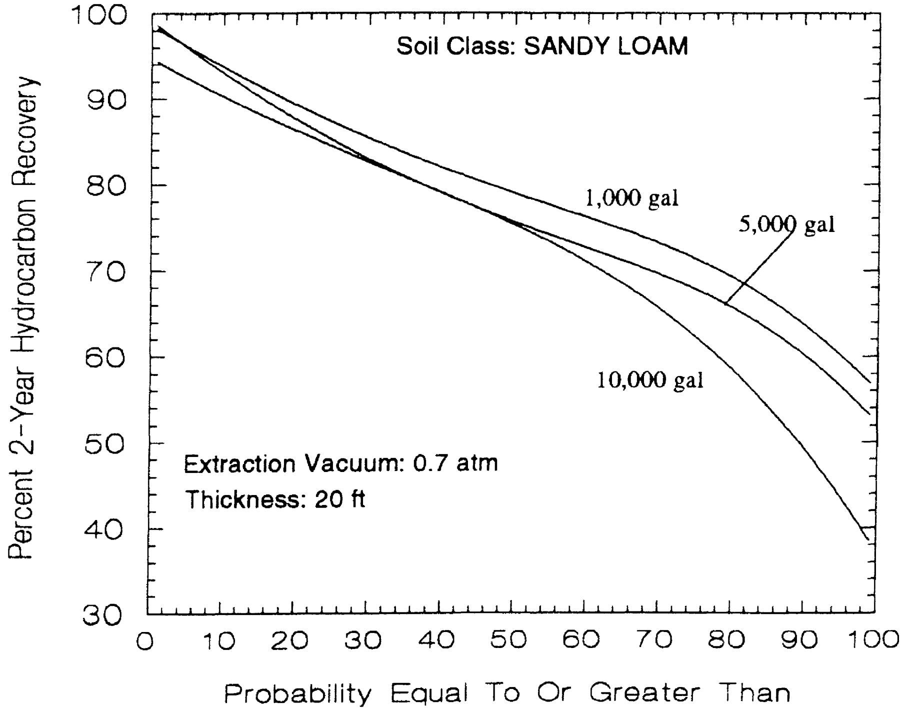
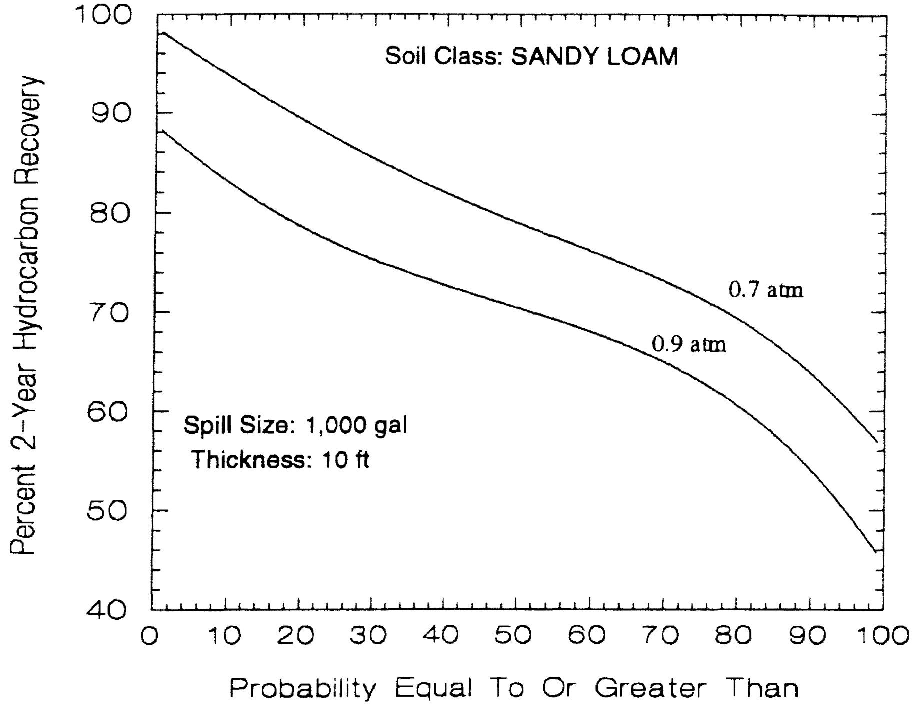


Figure 35. SANDY LOAM SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.7 atm vacuum at 10 and 20 foot thickness.



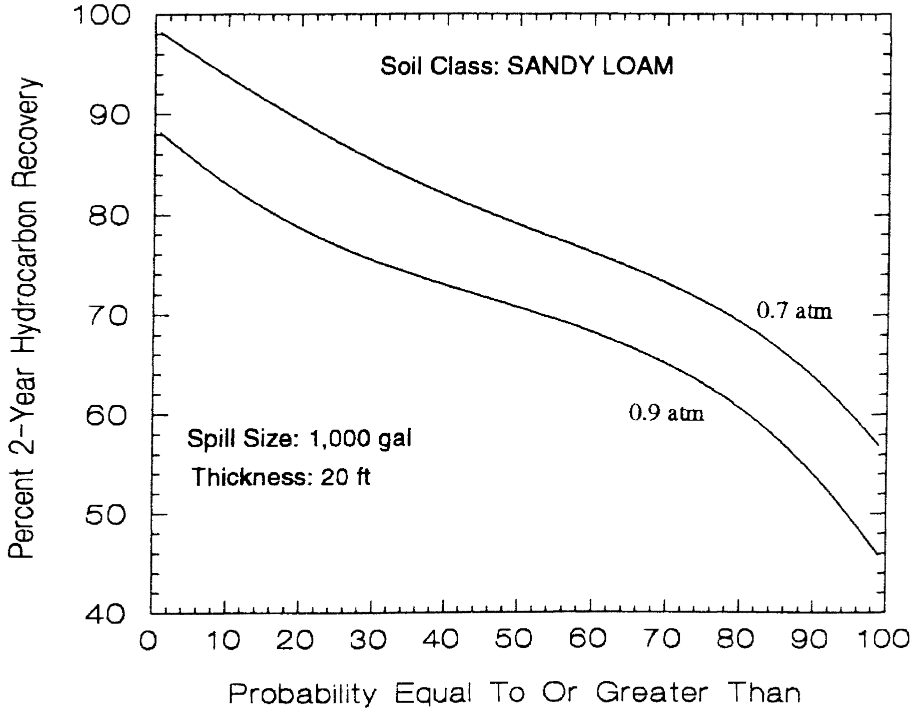


Figure 36. SANDY LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 1,000 gal composite gasoline spill at 10 and 20 ft thickness.

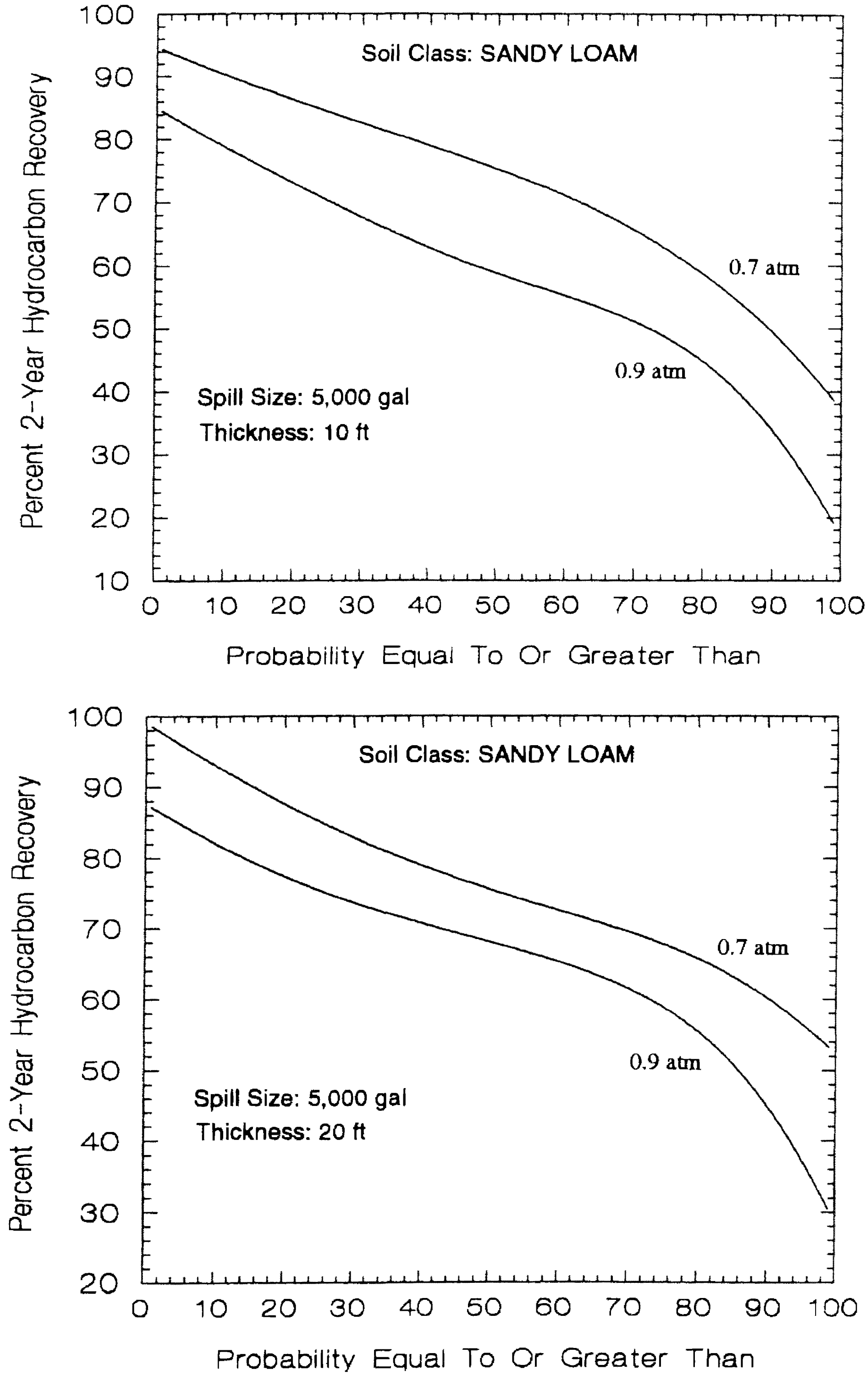
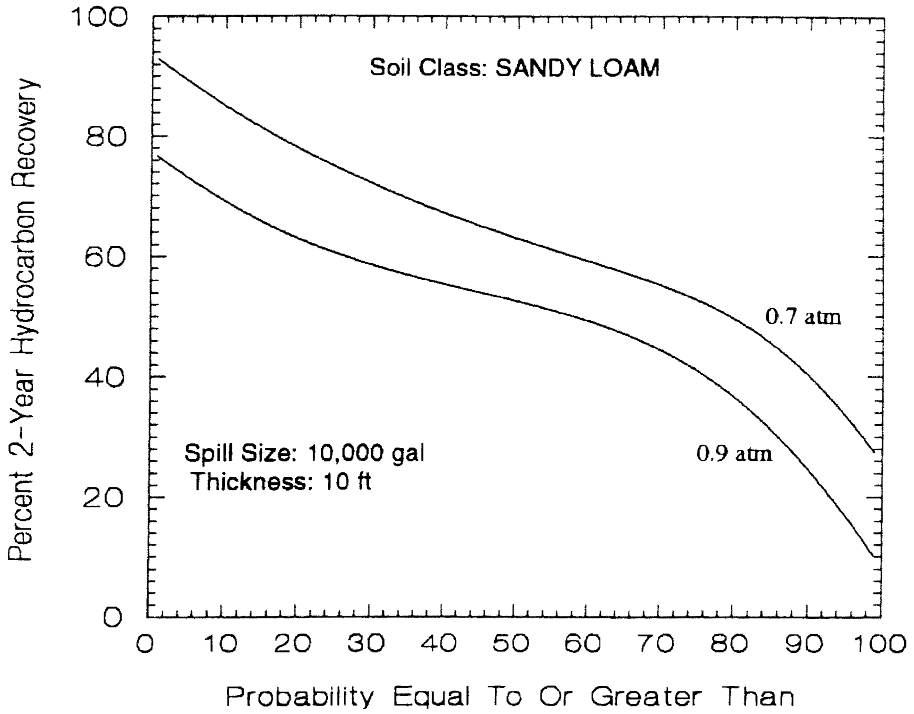


Figure 37. SANDY LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 5,000 gal composite gasoline spill at 10 and 20 ft thickness.



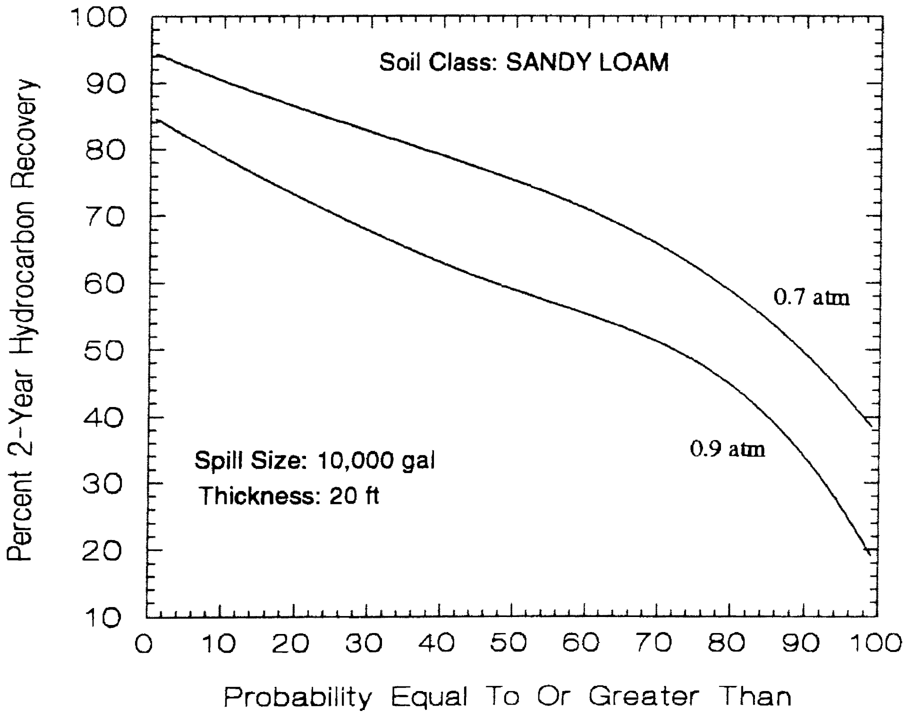


Figure 38. SANDY LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 10,000 gal composite gasoline spill at 10 and 20 ft thickness.

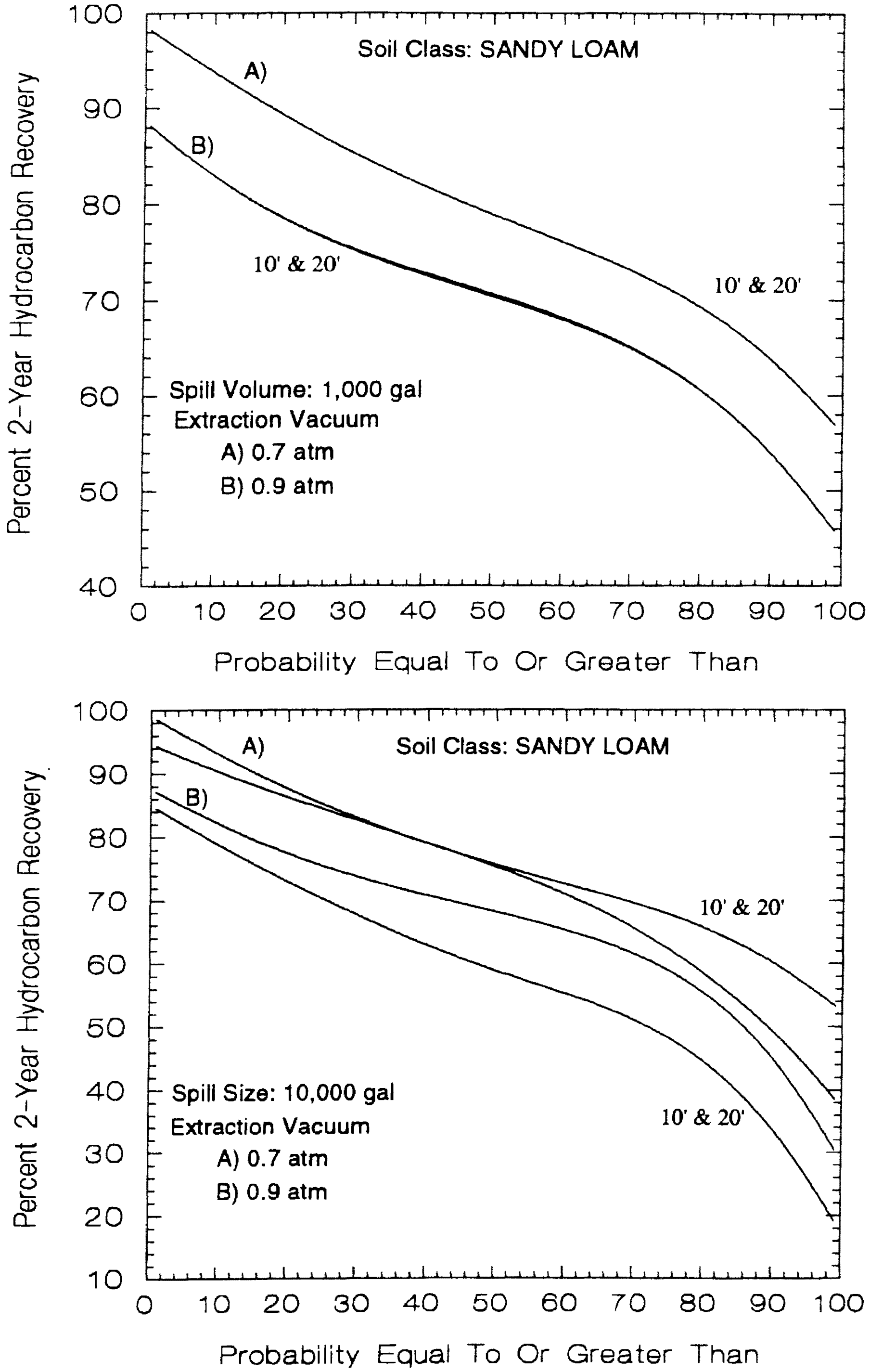


Figure 39. SANDY LOAM SOIL control variable analysis plots for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery using 0.7 and 0.9 atm vaccum at two spill sizes.

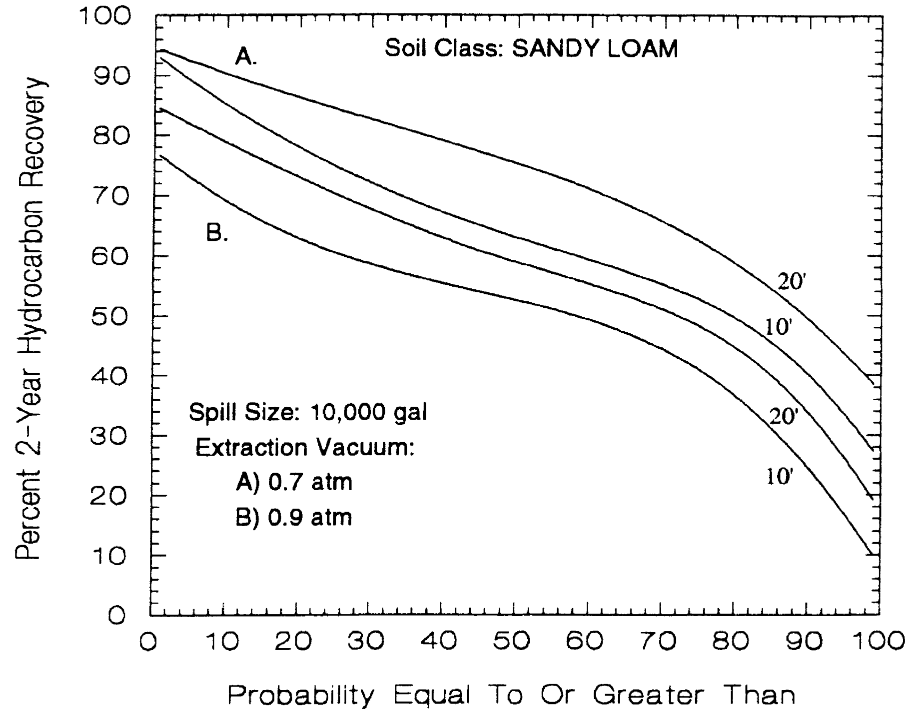
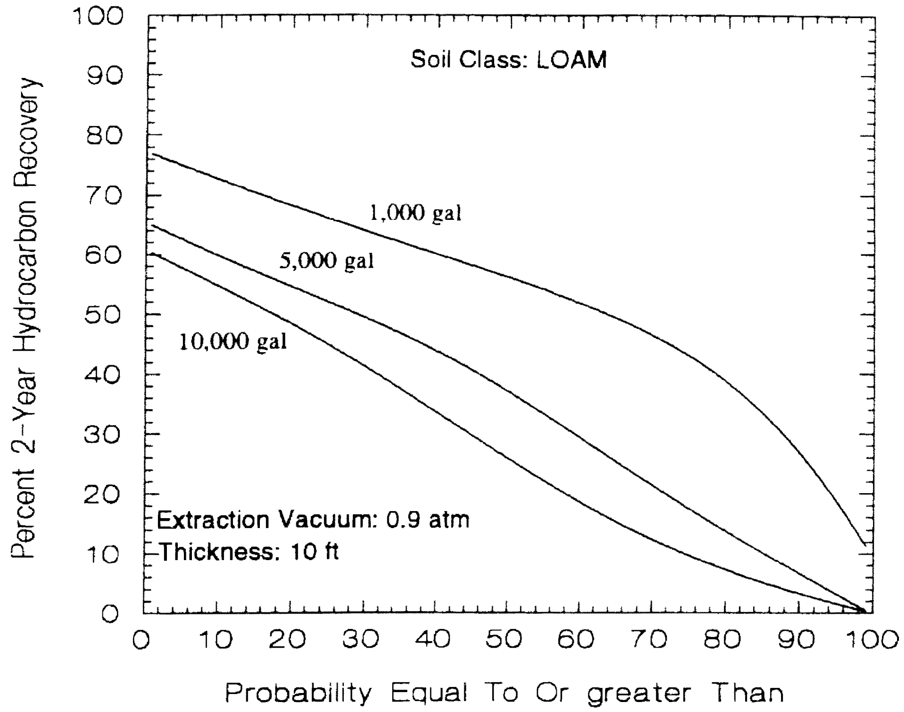


Figure 40. SANDY LOAM SOIL control variable analysis plots for contaminant thickness showing the effect on 2-year percent hydrocarbon recovery using 0.7 and 0.9 atm vaccum at 10,000 gallon spill size.

APPENDIX K

LOAM PARAMETER PROBABILITY PLOTS



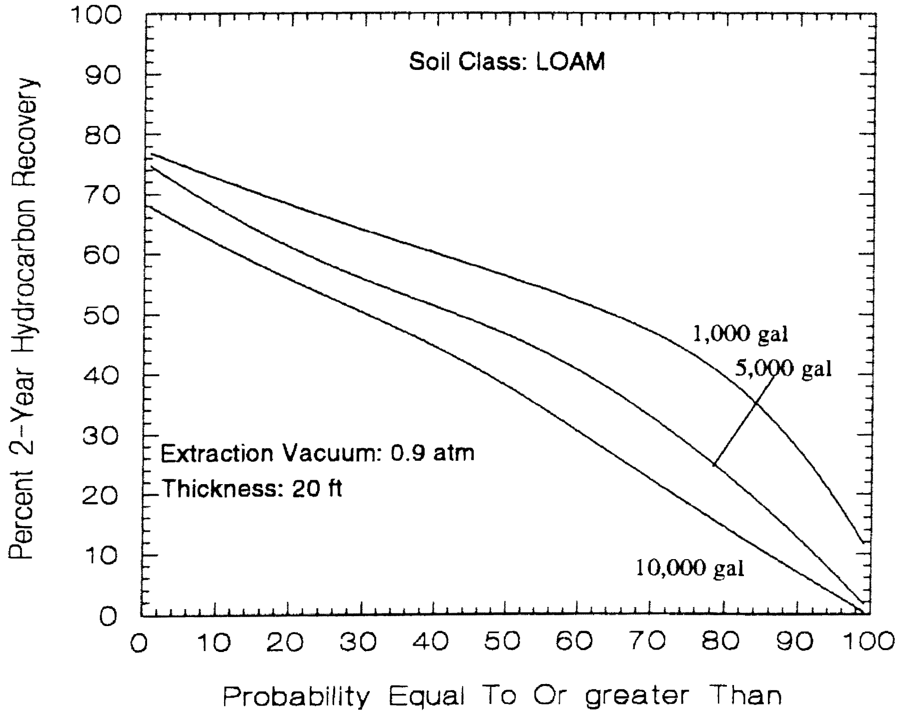


Figure 41. LOAM SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.9 atm vacuum at 10 and 20 foot thickness.

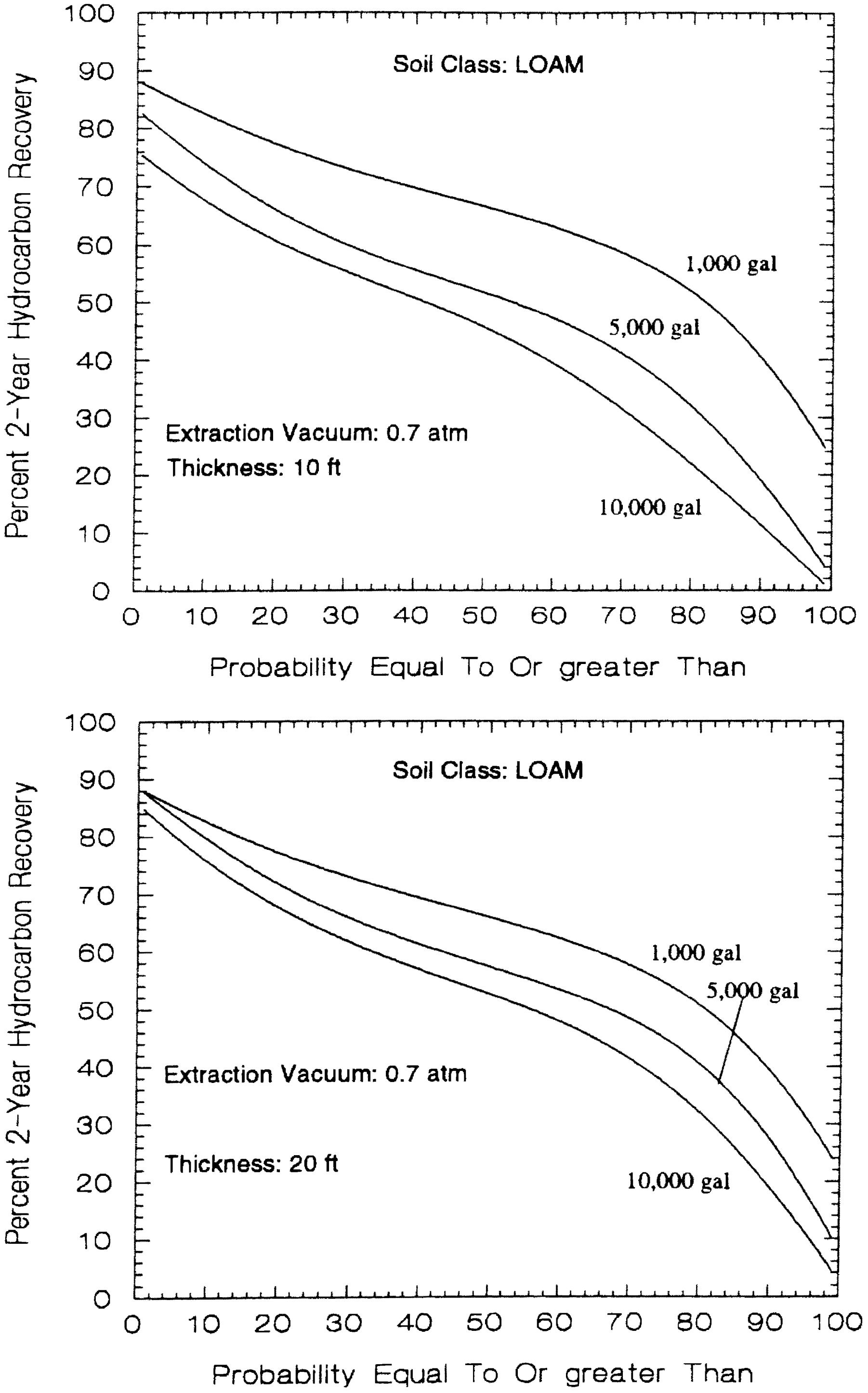


Figure 42. LOAM SOIL control variable analysis plots for spill size showing the effect on 2-year hydrocarbon recovery using 0.9 atm vacuum at 10 and 20 foot thickness.

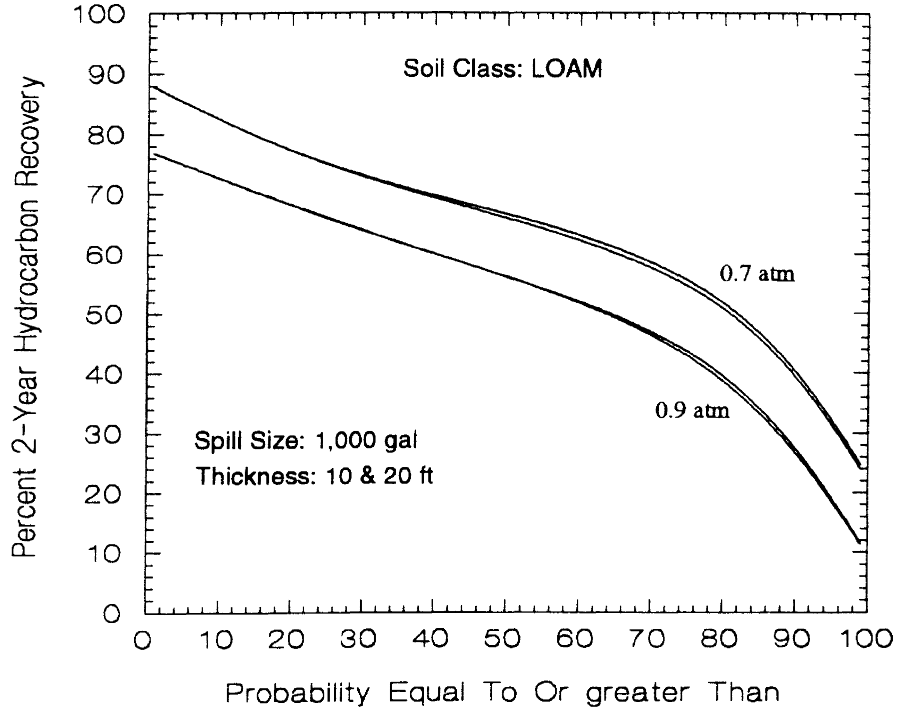


Figure 43. LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 1,000 gal composite gasoline spill at 10 and 20 ft thickness.

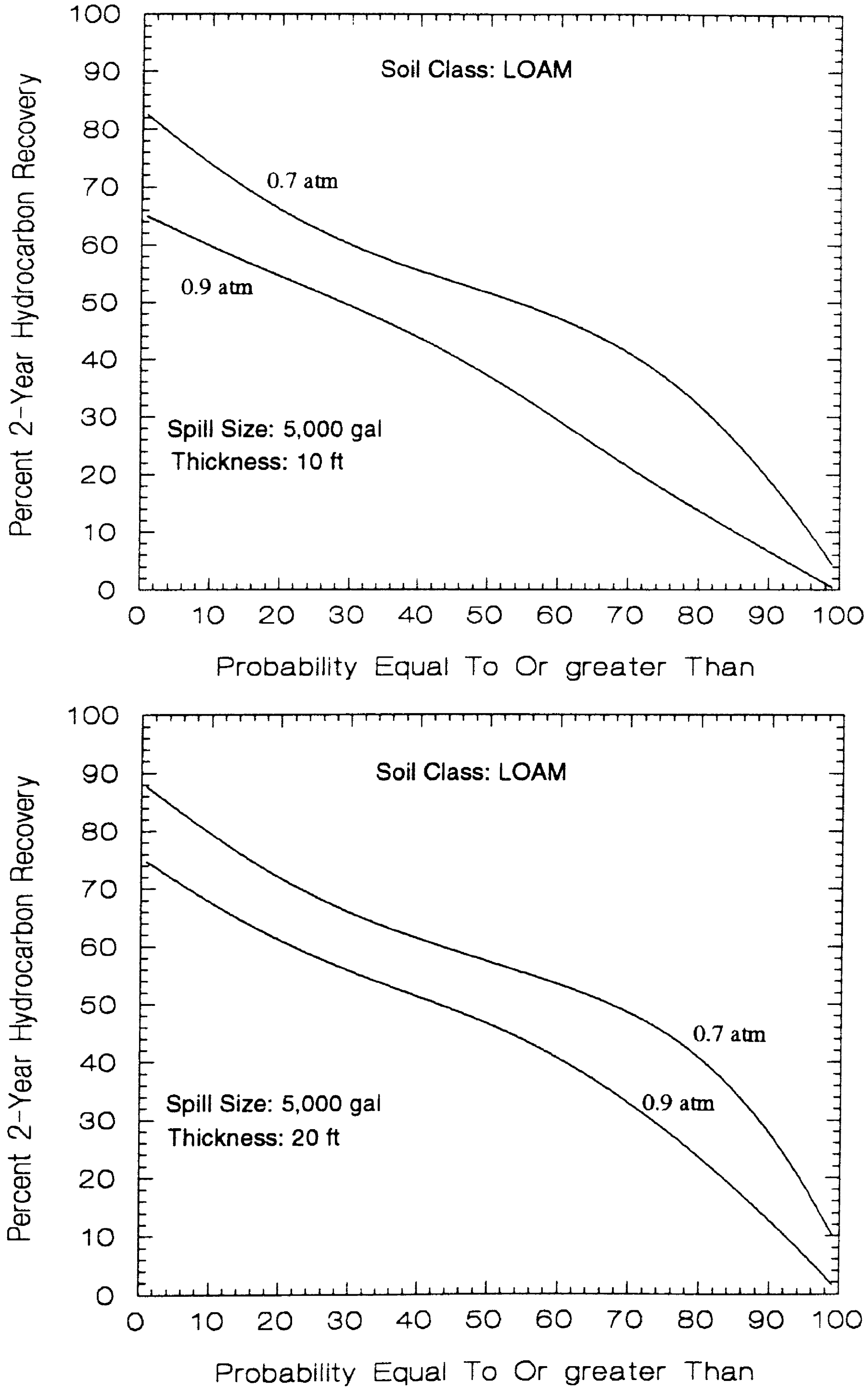
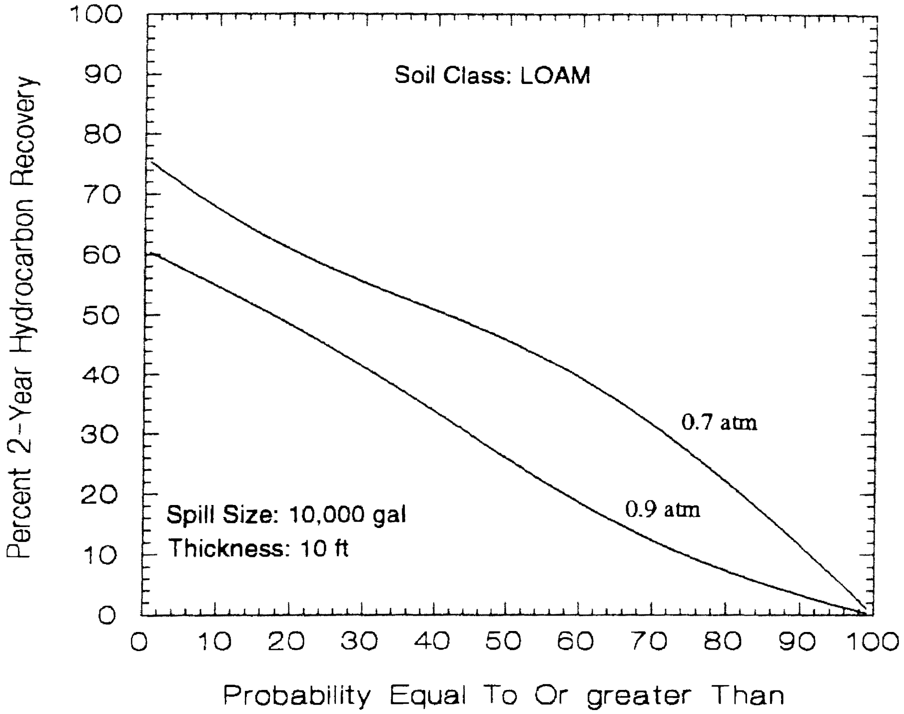


Figure 44. LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 5,000 gal composite gasoline spill at 10 and 20 ft thickness.



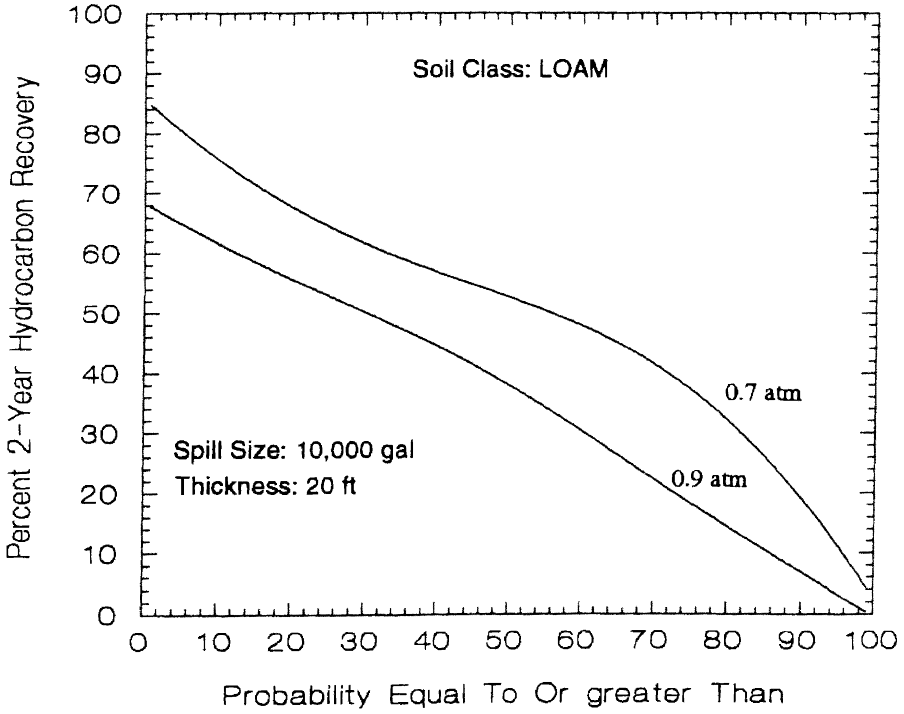


Figure 45. LOAM SOIL control variable analysis plots for extraction vacuum showing the effect on 2-year hydrocarbon recovery of a 10,000 gal composite gasoline spill at 10 and 20 ft thickness.

VITA

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