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A PROBABILITY BASED SCREENING TOOL TO ESTIMATE SOIL VENTING EFFICIENCIES

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ABSTRACT

This research developed a series of probability plots identifying the efficiencies of soil vapor extraction (SVE) as a function of soil type, spill size, and vacuum applied. The technique employed involved modifying an agronomic soil moisture model to further simulate air permeabilities for the various soils investigated. Probability density functions were developed for these permeabilities as well as for the expected BETX and Total Hydrocarbon recoveries. Comparisons to other approaches showed the method to be valid while providing a full range of probabilities for each of the metrics of concern.

INTRODUCTION

As much as forty-two million liters of gasoline are estimated to leak to the subsurface each year [1]. Current remediation strategies recommend rapid cleanup of these spills from the unsaturated zone. 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 in varying geological and chemical regimes [2-9].

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

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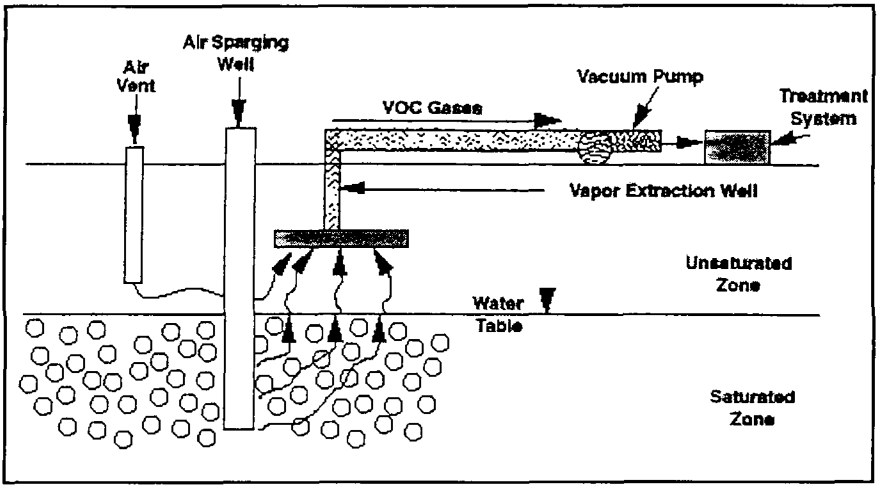


Figure 1. A combined soil vapor extraction/air sparging system. **Source:** [9].

and passes through the soil, volatizing liquid phase (and other phase, 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 until all condensed and gaseous phases are removed. Over the years 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 [4].

If the process is not properly applied, however, the cost savings associated with soil venting may be quickly lost due to protracted remediation times or the inability to comply with cleanup standards. Recent studies have shown that the key factors in venting performance were air flow and mass removal rates [5].

More specifically, Johnson et al. [5] found that the largest uncertainty in air flow calculations was caused by variations in a soil's air permeability. Their work showed that contaminant recovery became a function of the volume of the vapor mobilized per unit of initial mass of the material. This means that a doubling of the air flow rate also doubled the mass removed per unit time.

Due to the extreme variability within and between soil types, adequate estimates of air permeability are often difficult to obtain without costly specialized lab or field testing. The most typically recommended approach is the in-situ pump test [5] which, unfortunately, is generally unavailable for preliminary screening level analyses. 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 are available.

This article reports upon efforts to predict key soil parameters necessary to define the cumulative density functions for air permeability as a function of soil textural class. A readily available one dimensional numerical soil venting model was then used in conjunction with these parameter distributions to develop a more robust SVE screening tool.

PROCESS BACKGROUND

Determination of Critical Soil and Operational Variables

Air Flow Rate

Equation 1 presents the analytical one-dimensional radial gas flow model employed in this effort. This model, while oversimplifying air flow through porous media is commonly accepted for initial design and has been employed in many public and proprietary codes to provide screening level estimates of required air flow rates. Within the goals of this research, to develop a screening level methodology, Equation 1 was considered to be an appropriate approximation of subsurface dynamics.

Permeability was viewed as a random variable while system or operational variables included extraction well radius, radius of influence, and applied vacuum. The soils literature contains numerous assessments documenting the variability of hydraulic properties and permeability with textural characteristics of soils [11-13]. Permeability is by far the most uncertain and variable of the typically measured soil parameters. Depending on textural content, its absolute value can range widely over more than ten orders of magnitude and each soil type may have permeability ranges over two to four orders of magnitude [14]. In addition significant overlap of permeability values between soil types can be found. Because most permeability guidelines tend to be very general, significant uncertainty is introduced when permeability values are estimated from the literature.

$$Q = \pi H \frac{k_a}{\mu} P_w \frac{[1 - (P_{atm}/P_w)^2]}{\ln(R_w/R_1)} \tag{1}$$

k_a = soil air permeability (L^2)
μ = viscosity of air ($M\,T^{-1}\,L^{-1}$)
P_w = absolute pressure (vacuum) at extraction well ($M\,L^{-1}\,T^{-2}$)

P_{atm} = absolute ambient pressure ($M\ L^{-1}\ T^{-2}$)
R_w = radius of vapor extraction well (L)
R_I = radius of influence of vapor extraction well (L)
H = height of well screen (L)

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:

$$\frac{dM_i}{dt} = \eta\ QC_i^{eq} \tag{2}$$

where:
M_i = total number of moles of component *i* in the soil (mole)
Q = total gas flow rate through the contaminated zone (L^3T^{-1})
$C_i eq$= 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 that 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.

RESEARCH STRUCTURE

The subject research focused upon the development of a probability based screening tool which utilized randomly generated soil properties to calculate cumulative density functions describing air permeabilities for several soil types. These air permeabilities were then input to venting models to evaluate contaminant removal efficiencies. Soil textural classes and key system or management variables (referred to as incremental variables) were identified. Incremental variables, as determined from Equations 1 and 2, were those parameters other than air permeability which could have a pronounced effect on venting efficiencies. These were determined to be extraction vacuum, spill size, and contaminant zone thickness. Taken together these incremental variables were selected 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 defined a different scenario or management alternative for which contaminant removal was measured.

A range of probability defined air permeabilities for each of four different soil types was 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 hydrocarbon (TH) 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. These soil types were selected because they constitute the largest range of soils where SVE is potentially viable in terms of recovering contaminants within reasonable operating times.

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 TH and/or individual constituents) for any given site. Additional disaggregation or regrouping 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 was employed which allowed efficiency comparisons for intermediate values of incremental variables. Figure 2 presents the overall research structure used in this effort.

DEVELOPMENT OF SOIL DATA AND PERMEABILITY ESTIMATIONS

A method of estimating probability density functions for soil-saturated hydraulic conductivity and other hydraulic parameters previously developed by Carsel and Parrish [15] was modified to produce air permeability estimates. The Carsel and Parrish method employed a multiple regression equation originally developed by Rawls and Brakensiek [16] for estimating water content, saturated hydraulic conductivity and two water retention parameters (α and N) at a given pressure head using the saturated water content and the percentages of sand and clay in a soil. For this effort, the statistical distributions developed by Carsel and Parrish [15] were randomly accessed to provide soil-water properties for each of the four soil textures selected.

Soil Air Permeability Calculations

Permeability varies as a function of a soil's intrinsic permeability, fluid saturation, liquid content, and air porosity [17]. Air permeability was indirectly

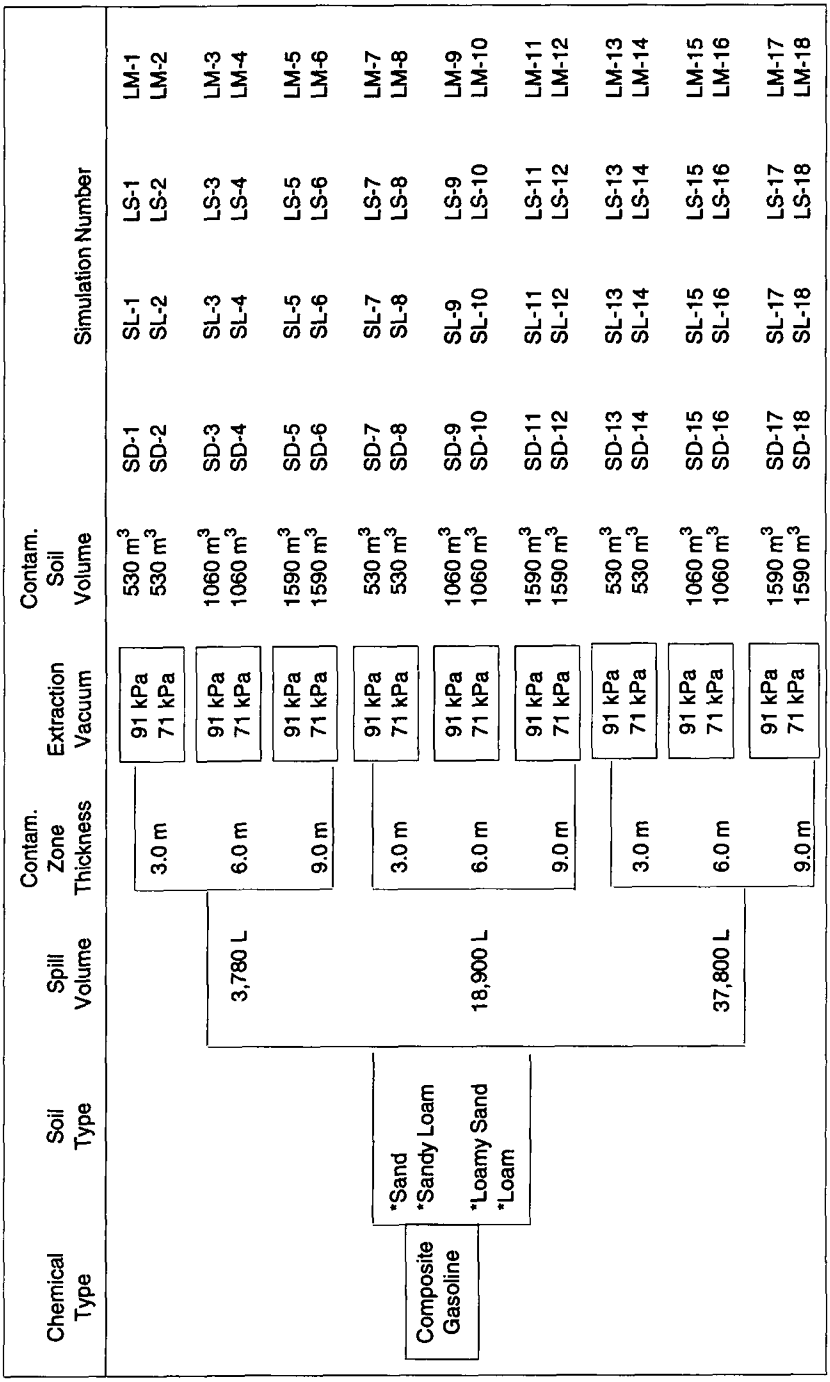


Figure 2. Flow chart showing research structure and overall range of spill site variables.
Note: SD = sand, SL = sandy loam, LS = loamy sand, LM = loam

estimated using the previously generated random saturated hydraulic conductivity values and van Genuchten water retention parameters (α, N) obtained from the Carsel and Parrish effort. The relationship between saturated hydraulic conductivity and intrinsic permeability is given by:

$$k_i = \frac{\eta_w k_s}{\rho_w g} \tag{3}$$

where:

k_i = intrinsic permeability ($L\ T^{-1}$)
η_w = viscosity of water ($M\ L^{-1}\ T^{-1}$)
P_w = density of water ($M\ L^{-2}$)
k_s = saturated hydraulic conductivity ($L\ T^{-1}$)
g = gravitational acceleration ($L\ T^{-2}$)

Equation 3 will yield soil permeability at 100 percent 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. The ratio of the effective or actual permeability at a given saturation to the intrinsic permeability is the relative permeability [17]. 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 personality 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. Air saturation was estimated as the difference between total porosity and water content [18]. Total porosity was assumed to equal total water saturation which was estimated from a set of normally distributed values that were then randomly assigned to each permeability realization. Means and standard deviations used to calculate the normally distributed saturated water content values for each soil class were taken from the U.S. National Resources Conservation Service data as reported by Carsel and Parrish [15]. Additionally, unsaturated zone soil moisture was taken at field capacity for all permeability calculations.

Assumptions of long-term steady state conditions were consistent with the typical practice of employing artificial ground cover during venting operations. Ground cover, 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 [19] model for predicting soil water content as a function of pressure head shown in Equation 5:

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

where:

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

Pressure head at field capacity was estimated at 355 cm [19]. Field capacity varied for each permeability realization as a function of the random soil properties, N, α, and Θ_r.

SOIL VENTING SIMULATIONS

To analyze the effect of air permeability on venting efficiency, a series of soil venting simulations over a range of soil and operational conditions was performed. The simulations were constructed to reflect what might typically be encountered at actual UST or other cleanup sites. The flow chart shown in Figure 2 identified the specific operational data and site conditions which were incrementally adjusted and modeled, as well as the simulation framework followed for each soil class. A total of twelve different scenarios was simulated for each of four soil classes for a total of forty-eight simulations. Each simulation involved repetitive sampling of the air permeability cumulative density function within a Monte Carlo framework.

A proprietary, but readily available code, Venting 2 was used to simulate the venting process [20]. This program was based on a series of analytical formulae developed by [21] and solves Equations 1 and 2 by finite differences to compute the total recovery and individual component recoveries versus time. It also computes the phase distribution and soil concentration of the remaining hydrocarbon for the specified venting conditions. The model has been previously tested against both field and lab data and found to adequately predict results for both weathered and fresh gasoline compositions [21]. This model was chosen as it is representative of those available for screening level design.

Chemical File—Development of Composite Gasoline

"Gasoline," a generic name for a complex mixture of as many as 180 hydrocarbon compounds consisting of alkanes, alkenes, naphthenes, and aromatics, was selected for evaluation in this effort [22]. While the majority of these compounds are present in contaminated unsaturated zones in relatively dilute concentrations, a few, however, do occur in large enough concentrations to pose a health risk or are under regulatory control. It was these compounds which were 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 file was created as the contaminant to be modeled. From a possible 180 components, nine were selected to represent a typical unleaded gasoline. These 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 [1]. It is also consistent with previous modeling efforts [18, 23]. Table 1 presents a comparison of concentrations used in this study and those most frequently reported in natural and composite gasolines.

Individual chemical properties of the composite gasoline used in this study are shown in Table 2. 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 molecular weight fractions. In this

Table 1. Comparison of the Major Component Concentrations Reported in Natural and Simulated Gasolines

	Concentration (mass %)						
Compound	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:
A. Natural gasoline [25]
B. API PS-6 gasoline [1]
C. Synthetic gasoline [26]
D. "Typical" regular gasoline [23]
E. "Typical" commercial gasoline (weighted average) [22]
F. Average of six unleaded gasolines [27]

way the regulated materials as well as the TH behaved in a manner consistent with more complex mixtures when soil venting was simulated.

Target Remediation Levels

A survey of regulatory requirements, based on data from forty states, indicated that these state agencies used TH as one metric soil contamination resulting from a spill or tank leak of petroleum products [24]. Thirty-four states also used TH either as guidance level for cleanup or as a site-specific remediation goal. The majority of states required 1000 ppm or less with a 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 Tables 2 and 3. 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 [18]. Based on these regulatory

Table 2. Selected Physio-Chemical Properties (at 20°C) of the Composite Gasoline Used in This Study[a]

Representative Compound	Concentration (% w/w)	Mole Weight (g/mol)	Boiling Point (°C)	Vapor Press. (kPa)	Solubility (mg/l)	Kow
Light-End	38.7	78.3	41.6	85	45	8,806
MTBE[b]	5.30	88.1	55.2	33	51,000	17.4
N-Hexane	3.73	86.2	69	16	13	8,710
Benzene	1.77	78.11	80	10	1,780	135
Toluene	7.32	92.14	111	2.90	515	490
Ethylbenzene[c]	1.91	106.17	136.2	0.93	152	1,410
P-Xylene	4.70	106.17	138	0.87	198	1,413
M-Xylene	3.30	106.17	139	0.81	162	1,585
O-Xylene	2.10	106.17	144	0.6	175	589
Heavy-End	31.2	131.1	174.9	0.26	32	60,034

[a]Ref. [23] except for concentrations from Table 3.
[b]Ref. [29]
[c]Ref. [28, Appendix A]

Table 3. Descriptive Statistics for Calculated Soil Air Permeabilities (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

Note: *S.D.* = standard deviation, CV = coefficient of variation

considerations, all venting simulations were run for five years or until TH was less than 500 ppm with individual components completely recovered.

RESULTS AND DISCUSSION

Monte Carlo Results

Sample Size

A total of 720 permeability realizations were completed for each of the four soil classes. Means and standard deviations of the air permeability were calculated and plotted as a function of increasing sample size. This served as a check on the adequacy of the random sampling effort as convergence of the data to near constant values was accomplished after approximately 250-300 realizations. Constant values indicate that the data sets were sufficiently large enough to ensure precision. Table 3 presents the summary statistics for these Monte Carlo simulations.

Determination of Probability

Air permeability probabilities within each soil type were determined using the Weibull plotting position formula: ordered rank position divided by sample size plus one. Air permeability probability within each soil class was then determined from normal probability plots of the data. Each plot was made using 720 air permeability realizations generated for each soil class.

After the air permeability distribution was determined for each soil class, the range of probabilities from 1 to 99 percent was selected from the theoretical best fit line from each plot. These values are presented in Table 4. The smallest permeability range occurred in the sand soil, which varied by only one order of magnitude while loam had the largest variation. While it is apparent that some permeability values were present in all soil classes the likelihood of these same permeability values occurring in all soil types varied widely. For example, in a sand soil a 2.50 darcy permeability had 60 percent probability of occurrence

Table 4. Magnitude and Probability of Air Permeability (Darcy) by Soil Class

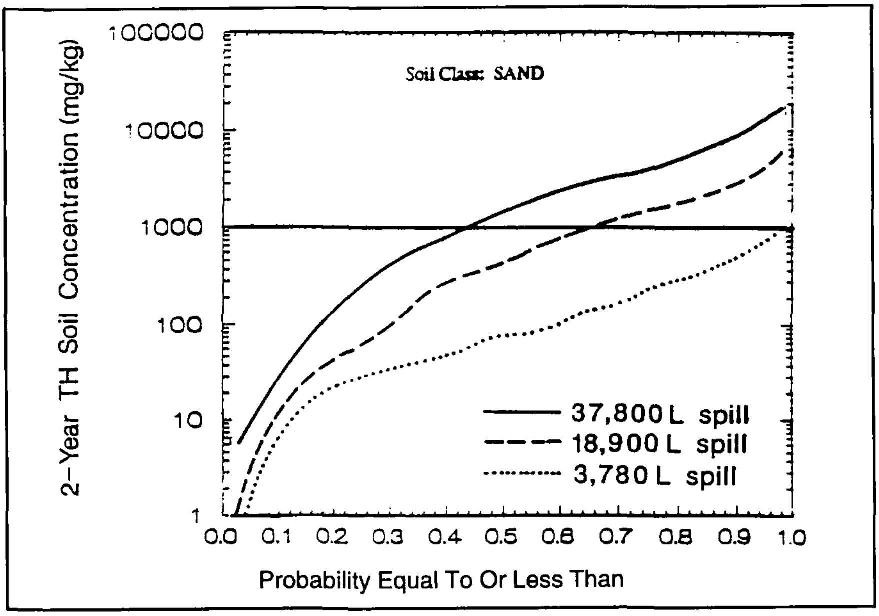
Probability of (x) Equal or Greater Than (%)	Sand	Loamy Sand	Sandy Loam	Loam
1	7.42	5.80	2,32	0.610
10	5.78	3.34	1.08	0.300
20	4.82	2.66	0.655	0.140
30	4.07	1.93	0.430	0.081
40	3.44	1.40	0.306	0.050
50	2.88	1.03	0.225	0.033
60	2.50	0.77	0.156	0.021
70	2.12	0.52	0.114	0.013
80	1.64	0.34	0.068	0.008
90	1.15	0.19	0.036	0.004
99	0.43	0.042	0.008	0.0004

while in a sandy loam soil the same approximate value would be expected to occur less than 1 percent of the time. This result further highlighted the problem with selecting a single air permeability value from standard tables.

Soil Texture Class Venting Probabilities

With this information it was readily possible to predict soil venting success based only on knowledge of spill size and soil type. This was accomplished by plotting probability of expected TH soil concentration as a function of spill size for each soil class (Figures 3 and 4). These plots generated by a distance weighted least squares method (DWLS) present the probability of achieving TH soil concentrations at the end of two years for 3,780, 18,900, and 37,800 liter gasoline spills. These probabilities were inclusive for all combinations of operational parameters considered and did not distinguish between individual variables. For example, a point on a 18,900 liter line which indicated 70 percent probability of achieving 1000 mg/kg included several combinations of screen length, extraction vacuum, and contaminated soil volume. The purpose of these plots was to serve as an initial screening tool to generally indicate whether soil venting was feasible (for a 2-year remediation). If venting appeared feasible, additional analyses would be undertaken to determine which combinations of operational parameters indicated the highest probability of success.

These and subsequent figures are probability based analogues to analyses developed by Johnson et al. [23] which utilized a dimensionless scaling to allow comparisons across alternative permeabilities. These figures provide similar



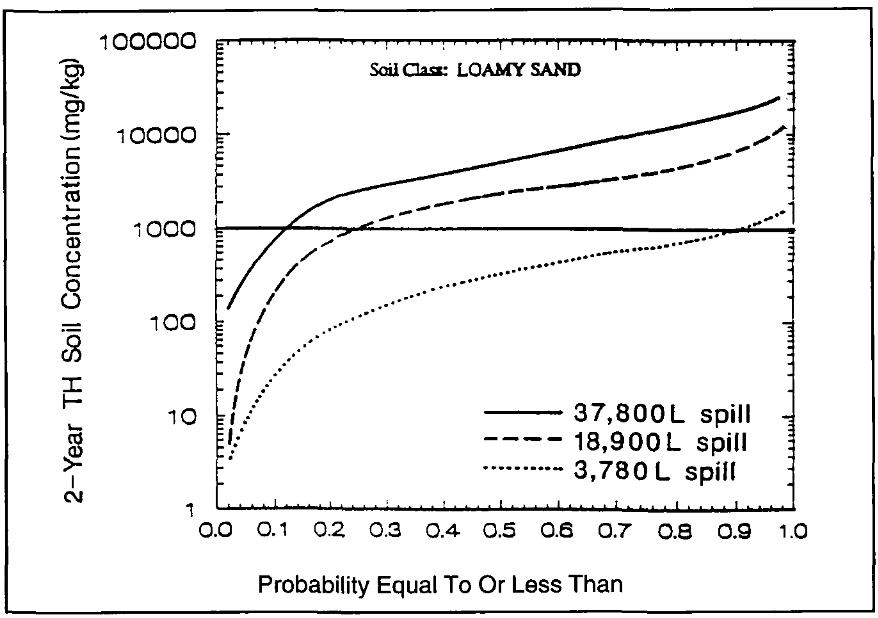
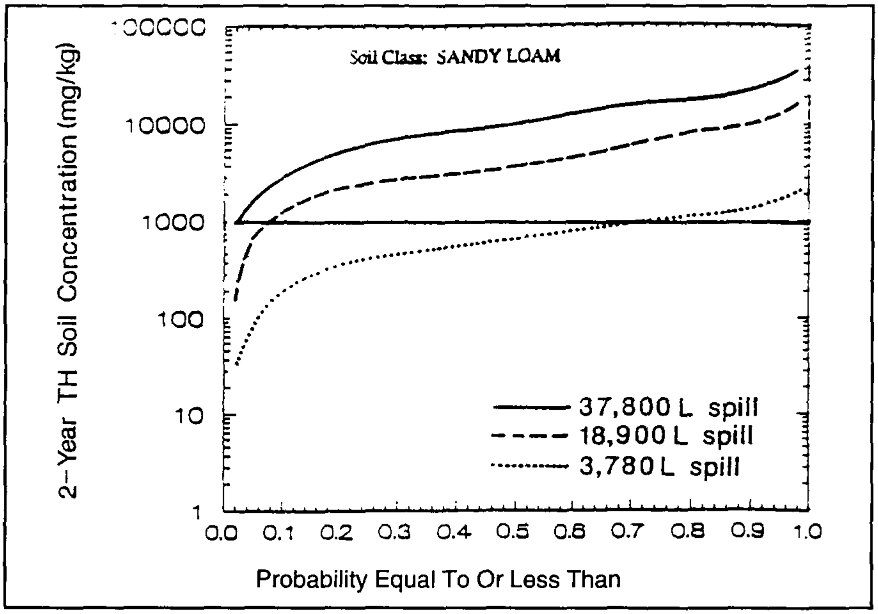


Figure 3. Probability of expected TH soil concentrations after a two-year venting period. Plots show results of all sand and loamy sand soil simulations.



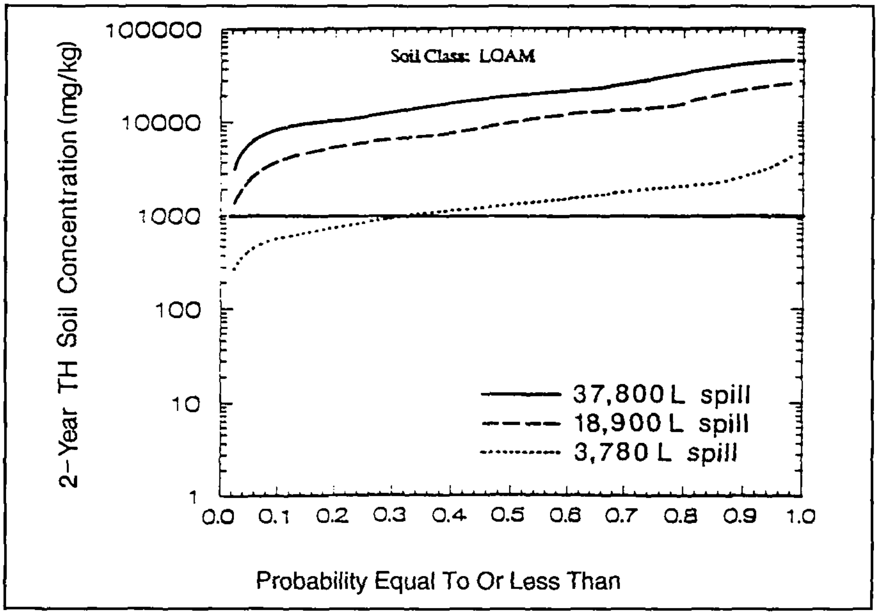


Figure 4. Probability of expected TH soil concentrations after a two-year venting period. Plots show results of all sandy loam and loam soil simulations.

information when accessed on an air flow per unit initial contaminant mass basis. Examination of Figure 4 and Table 4 shows that the points where each probability curve crosses the 1000 mg/kg standard correspond generally to the same amount of air utilized per initial mass. That is, the 37,800 liter spill line crosses at a permeability of about 4 darcys (40% probability) while the 18,900 and 3,780 liter spills intersected at about 2 and 0.4 darcys respectively, or about the same air to contaminant mass for each spill evaluated. This analysis directly supports the referenced work while also identifying probabilities of either permeability or air flow rate as defined by equation 1.

If the spill size was unknown, field estimates of initial TH concentration data could also be used to predict venting success. For the three spill sizes considered here, initial soil concentrations of TH (as calculated by the venting program) varied slightly from soil to soil due mainly to differing bulk density, water content, and porosity. Recalling that two contaminated zone thickness (screen lengths) were simulated, average initial TH soil concentrations for the 3,780 liter spill size simulations were 2,000 and 4,000 mg/kg respectively. The 18,900 liter spill simulations resulted in average initial TH soil concentrations of 10,000 and 20,000 mg/kg while the 37,800 liter spill simulations averaged 20,000 and 40,000 mg/kg.

To estimate the probability of venting success in this way, an initial TH concentration was substituted for spill size. If, for example, field data indicated a soil concentration of 7,500 mg/kg TH in a loamy sand soil. Since 7,500 mg/kg was between the range of 5,000 and 10,000 mg/kg, the 18,900 liter spill size curve was selected on the loamy sand soil plot (Figure 3) and probability was read at the desired TH concentration level. A line through the 1,000 mg/kg TH concentration level was drawn as an illustrative remediation goal to show relative efficiencies of soil venting at the various spill sizes. As expected, analysis of these plots indicated that soil venting success for all spill sizes was predicted to be highest in the sand soil (Figure 3) and lowest in loam soil (Figure 4).

Based on the results of these plots, soil venting was generally not recommended for spills in the 37,800 liter size range except in sand. The highest probability of success was 44 percent in the sand soil while the next highest was only 12 percent in the loamy sand (Figure 3). In sandy loam and loam soils there was virtually no chance to meet a 1000 mg/kg TH cleanup goal within a two-year period and other remediation alternatives should be investigated.

For medium size spills in the 18,900 liter range, soil venting could be pursued in the sand and loamy sand soils. In the sandy loam soil less than 10 percent of the simulations resulted in a soil TH reduction below 1,000 mg/kg. This indicated that, while possible, it was not probable that a spill of that magnitude would be remediated in two years in sandy loam. Soil venting for small spills in the 3,780 liter range could be recommended for all soils. Probabilities of reducing TH to 1,000 mg/kg varied from 99 percent in sand to almost 50 percent in loam soil. Similar analyses not presented here in the interests of space evaluated the effects of longer venting times on probabilities of success in loams and sandy loam soils. Generally, longer venting times of up to five years did not appreciably increase the probability of success for spills larger than 3,780 liters. For example, the two-year probability of success associated with a 37,800 liter spill in a sandy loam was approximately 4 percent. For a five-year venting period it only increased to approximately 15 percent. This indicated 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.

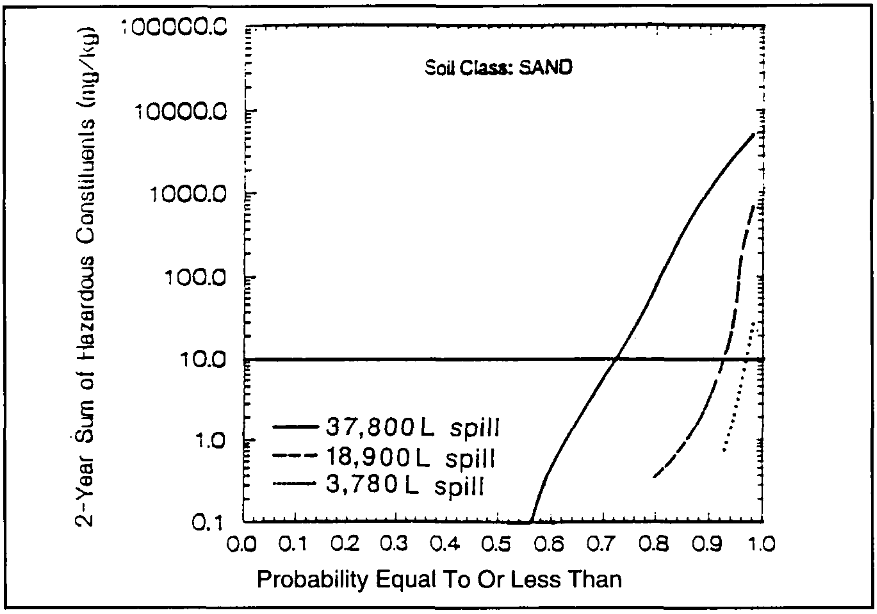
Individual Constituent Probabilities

An alternative to defining venting success with TH 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 TH and another for selected individual components which are usually related to BETX [24]. The composite gasoline that was used in this study was created to allow easy tracking of these constituents. Referring to Table 3, the individual components tracked in these venting models included BETX as well as MTBE and N-Hexane. For ease of discussion these components will, hereafter, simply be referred to as BETX. Although varying between states, the regulatory limit of the sum of the BETX constituents in soils is much lower than for TH. As a group, however, BETX is easier to recover than TH because it is generally much more volatile. If soil venting cleanup goals can be based on BETX alone, wider venting applications with higher probabilities of success are possible.

The probability plots for the recoveries of these BETX materials after a two year venting period are presented in Figures 5 and 6. These plots, when compared to Figures 3 and 4, the total hydrocarbon recovery probabilities, illustrate the effects of the higher BETX volatility upon contaminant capture. As an example, the probability of reaching 100 mg/kg TH in a loam for a 3,780 liter gasoline spill (Figure 4) was determined to be less than 1 percent. This compares to a 30 percent probability of recovering sufficient BETX to leave 10 mg/kg in the same loam soil.

Separate Probabilities

Prediction of the impact of the various operational parameters such as well spacing on the probability of venting success was provided by probability assessments for each combination of operational parameters. Figures 7 and 8 present the results for a sand soil. Similar plots for the other soil texture classifications are available from the authors. These plots may be used to evaluate which combination of operational parameters offered 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



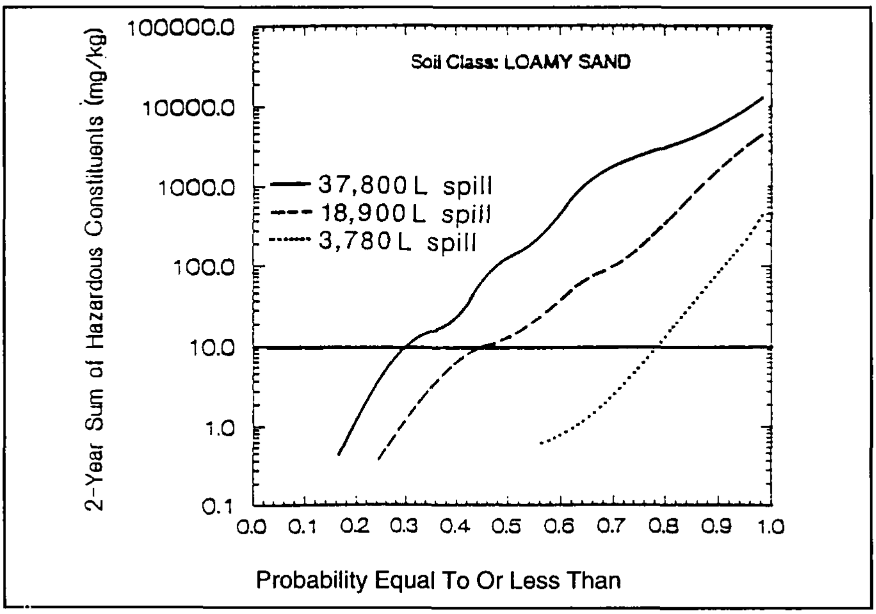


Figure 5. Probability of expected total BETX, MTBE, and N-Hexane soil concentrations after a two-year venting period. Plots show results of all sand and loamy sand soil simulations.

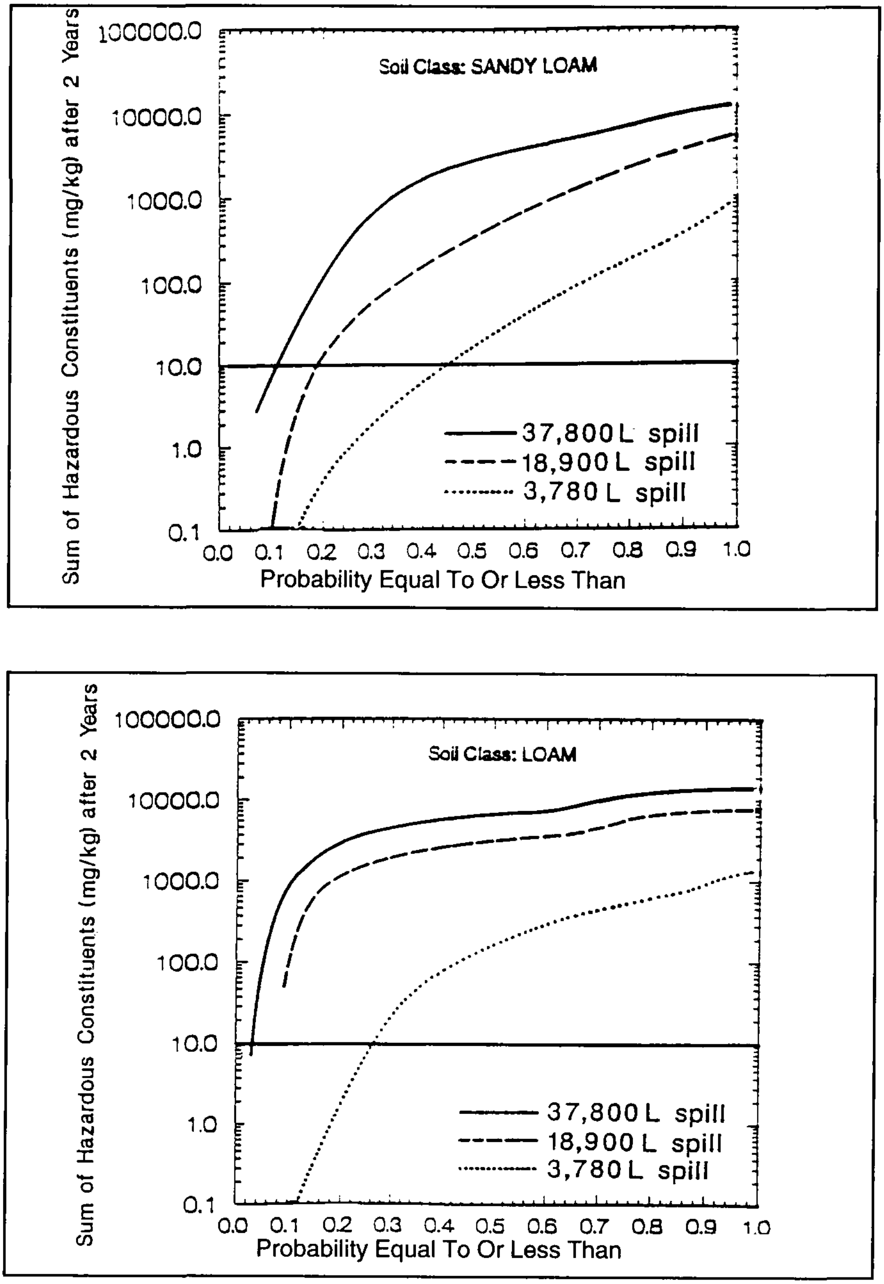


Figure 6. Probability of expected total BETX, MTBE, and N-Hexane soil concentrations after a two-year venting period. Plots show results of all sandy loam and loam soil simulations.

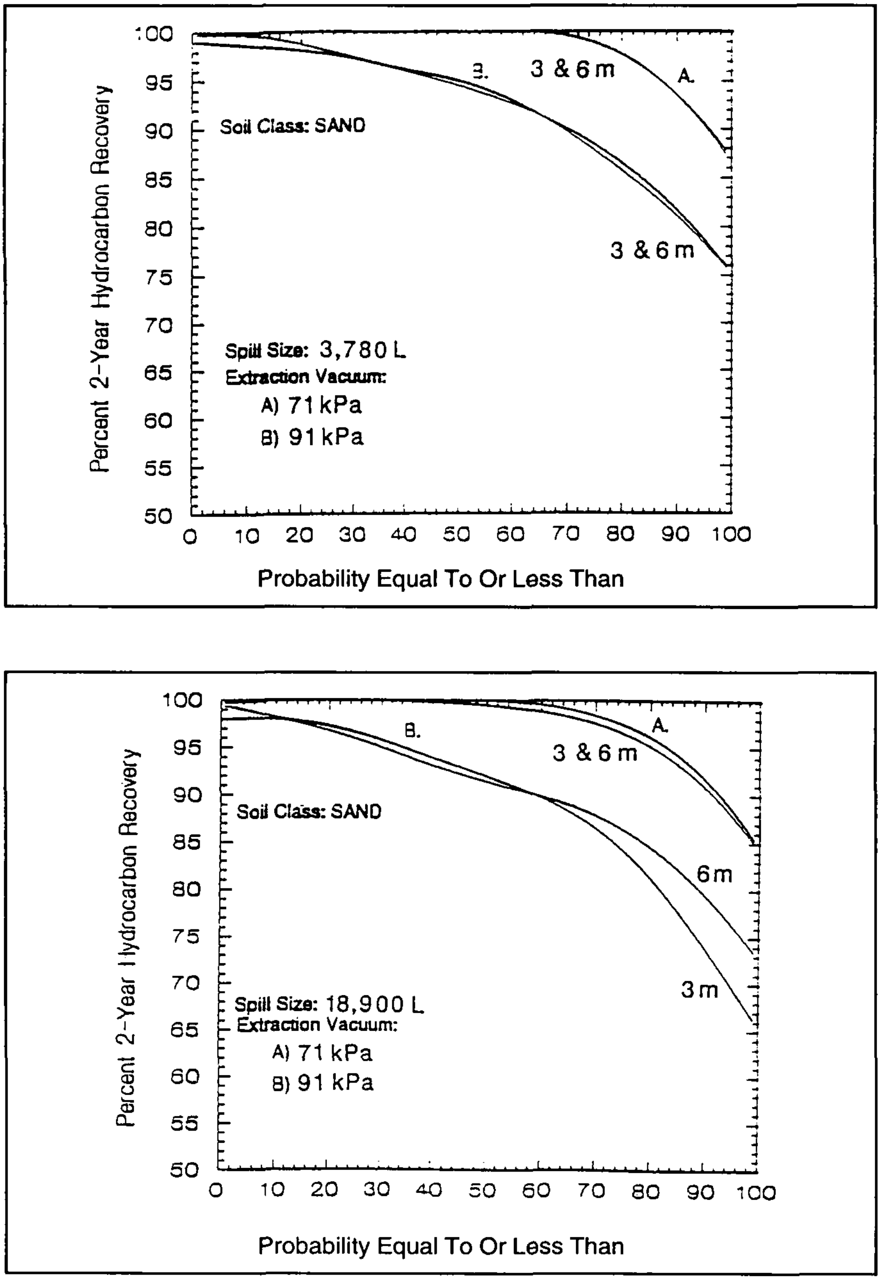


Figure 7. SAND soil control variable analysis plots for contaminant thickness showing the effect on two-year percent hydrocarbon recovery using 71 and 91 kPa vacuum at two spill sizes.

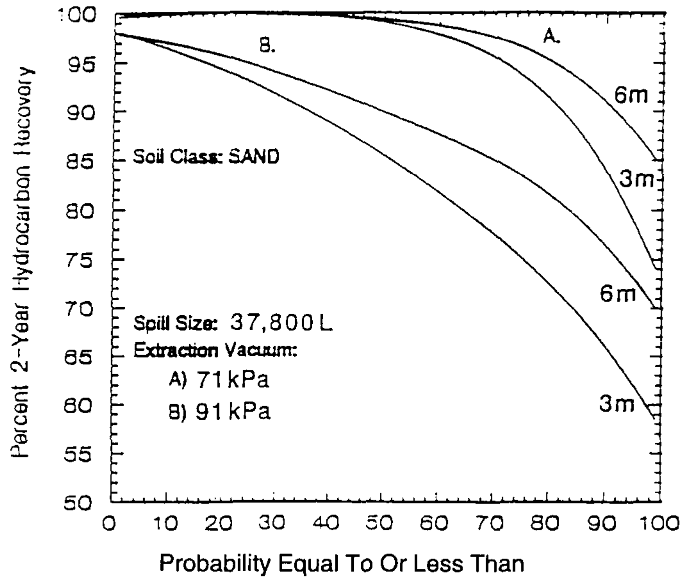


Figure 8. SAND soil control variable analysis for contaminant thickness showing the effect on two-year percent hydrocarbon recovery of a 37,800 liter spill at two extraction vacuum.

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.

Figures 7 and 8 indicated that venting success in sand soil (as well as all other soil classes) was most sensitive to extraction vacuum for all spill sizes and contaminant thicknesses. For example, when using 91 kPa extraction vacuum for 37,800 liter spill size over a 3 meter thickness there was a 50 percent probability that the percent hydrocarbon recovery was 85 percent, compared to 99 percent when using 71 kPa vacuum. Figure 7 indicates that even at the smaller spill size of 1,000 gallons, there was still a 6 percent difference of hydrocarbon recovery associated with the increased vacuum.

Generally, venting success was found to be less sensitive to the other operational or incremental parameters. The magnitude of this sensitivity varied mainly as a function of spill size. For instance, in Figure 7 the effect of contaminant thickness on expected hydrocarbon recovery for a 3,780 and 18,900 liter spill size was small, as noted by the minimal difference in percent hydrocarbon recovery between the 3 and 6 meter thickness curves.

Figure 7 can also be used to examine trade-offs in system design. This figure compares the effect of extraction vacuum on recovery of a 3,780 liter spill for 3 and 6 meter thickness. In the case of a 3 meter contaminant thickness with a cleanup goal of 1,000 mg/kg, the question becomes which extraction vacuum should be applied. Under the conditions upon which the simulation was based (refer to Figure 2), initial TH concentration was approximately 4,000 mg/kg based on a contaminated soil volume of about 530 cubic meters. Thus, to reduce TH to 1,000 mg/kg, about 75 percent hydrocarbon recovery is required. Entering the appropriate plot and reading at an 80 percent probability level, the 91 kPa extraction vacuum was expected to recover about 85 percent of the hydrocarbon compared to 97 percent for the 71 kPa extraction vacuum. Since the use of either vacuum would recover more than the 75 percent of the hydrocarbon required by the cleanup goal, the most economical design would be the 91 kPa extraction vacuum which should result in lower operating costs.

Interpolation of Intermediate Parameter Values

Intermediate spill sizes, screened intervals, and extraction vacuums may also be evaluated by interpolation of probability levels presented in these figures if a linear relationship is assumed. As an example, a 75 percent probability of the expected percent hydrocarbon recovery for a 28,500 liter gasoline spill in a sand soil with a 4.5 meter screened interval using a 81 kPa extraction vacuum involves the four probability plots which bracketed these operational and spill values as shown in Figures 7 and 8. Expected hydrocarbon recovery at the 75 percent probability level for a spill size of 28,500 liters was assumed to be located half the distance between the spill size curves for 18,900 and 37,800 liters. Reading from these plots, the values obtained were 96 and 97 percent and 80 and 85 percent. Double interpolation indicated that there was a 75 percent probability that at least 89.5 percent of the gasoline spill would be recovered during the two-year venting period. The same interpolation technique can also be used to define a screening level probability for other combinations of spill sizes and operational variables.

SUMMARY AND CONCLUSIONS

Successful applications of soil venting have been found to be highly dependent on the air permeability of the contaminated soil. Making adequate estimates of air permeability is often difficult without lab or field tests, thereby reducing the efficacy of pre-design screening or feasibility modeling.

A Monte Carlo approach based upon a modified agricultural soil-water modeling technology allowed the prediction of the magnitude and the probability of air permeabilities as a function of soil textural class. The results provided improved estimates of air permeability for initial designs and operations.

These probability indexed air permeabilities were then used in a publicly available numerical model to evaluate the performance of soil venting within each of four soil types. Soil venting evaluations were conducted for a composite gasoline over a range of commonly encountered site and operational conditions. In this manner a probability-based screening method to predict the success of soil venting based on soil textural classes was developed.

Decisions regarding remediation selection must sometimes be made in situations where only minimal data are available. In these situations probability-based guidelines provide a useful initial estimate of critical soil properties as well as a measure of expected contaminant recovery.

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