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ESTIMATION OF AIR IMPACTS FOR SOIL VAPOR EXTRACTION (SVE) SYSTEMS

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GUIDANCE STUDY SERIES

Estimation of Air Impacts for Soil Vapor Extraction (SVE) Systems

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INTRODUCTION

The U.S. Environmental Protection Agency's Office of Air Quality Planning and Standards and the Regional Air Offices have been given the responsibility to evaluate air impacts from Superfund sites. An important part of this program is the analysis of air impacts from various alternatives for cleaning up Superfund sites. Since these analyses are frequently required for planning purposes prior to actual cleanup they depend on estimated emissions and ambient concentrations rather than on field measurements.

This report provides procedures for roughly estimating the ambient air concentrations associated with soil vapor extraction (SVE). The procedures for SVE systems are analogous to procedures for air strippers that have previously been published[1]. SVE is also known as soil venting, vacuum extraction, aeration, or in-situ volatilization. It is a widely used technique for removing volatile organic compound (VOC) vapors from contaminated soil. Procedures are given to evaluate the effect of the concentration of the contaminants in the soil-gas and the extraction rate on the emission rates and on the ambient air concentrations at selected distances from the SVE system.

Health-based ambient air action levels are also provided for comparison to the estimated ambient concentrations. Many of the health levels have not been verified by EPA or are based on extrapolations of oral exposures or occupational exposures. Their indiscriminate use could either under or over estimate the potential health effects. The statements and conclusions presented in this report are those of the authors and do not reflect U.S. EPA policy.

PROCESS DESCRIPTION

Soil vapor extraction systems involve the removal of air containing volatile compounds from unsaturated soil. A general process schematic is shown in Figure 1. One or more extraction wells are placed in the vadose (unsaturated) zone at the site of the contamination. The extraction wells typically are constructed of slotted plastic pipe placed in permeable packing such as coarse sand. The wells are connected via a manifold that leads to an air blower or vacuum pump. The vacuum pump is used to withdraw air from the extraction wells and is typically capable of inducing a vacuum of about 30 in. Hg. The subsurface vacuum that is created and the resulting pressure gradient in the soil will dictate the rate at which vapors are withdrawn and the air flow patterns in the vadose zone.

As shown in Figure 1, air inlet wells can be used to introduce ambient air at the edge of the contaminated area. They serve to both increase the rate that contaminant-laden air is extracted and to control the direction of vapor migration. The air inlet wells can be passive or air can be forced into the ground using an air blower. Only a fraction of the extracted air comes from the air inlets, with the remainder of the air drawn from the surface through the soil. Therefore, it is important to have an impermeable cap in place at the top of each extraction well to prevent the direct inflow of ambient air down the well casing.

Several design options are available for increasing the air flowrate and removal efficiency of an SVE system. The inlet air can be heated to increase the partitioning of subsurface contaminants into the vapor-phase. The air blower used to inject air into the ground will heat the air to some extent due to compression; additional heat is added in some SVE systems by also injecting steam into the ground. In some cases, the air inlet wells extend down into the saturated zone. The inlet air bubbles up through the water table and this sparging action can enhance the removal of slightly soluble volatile organic compounds.

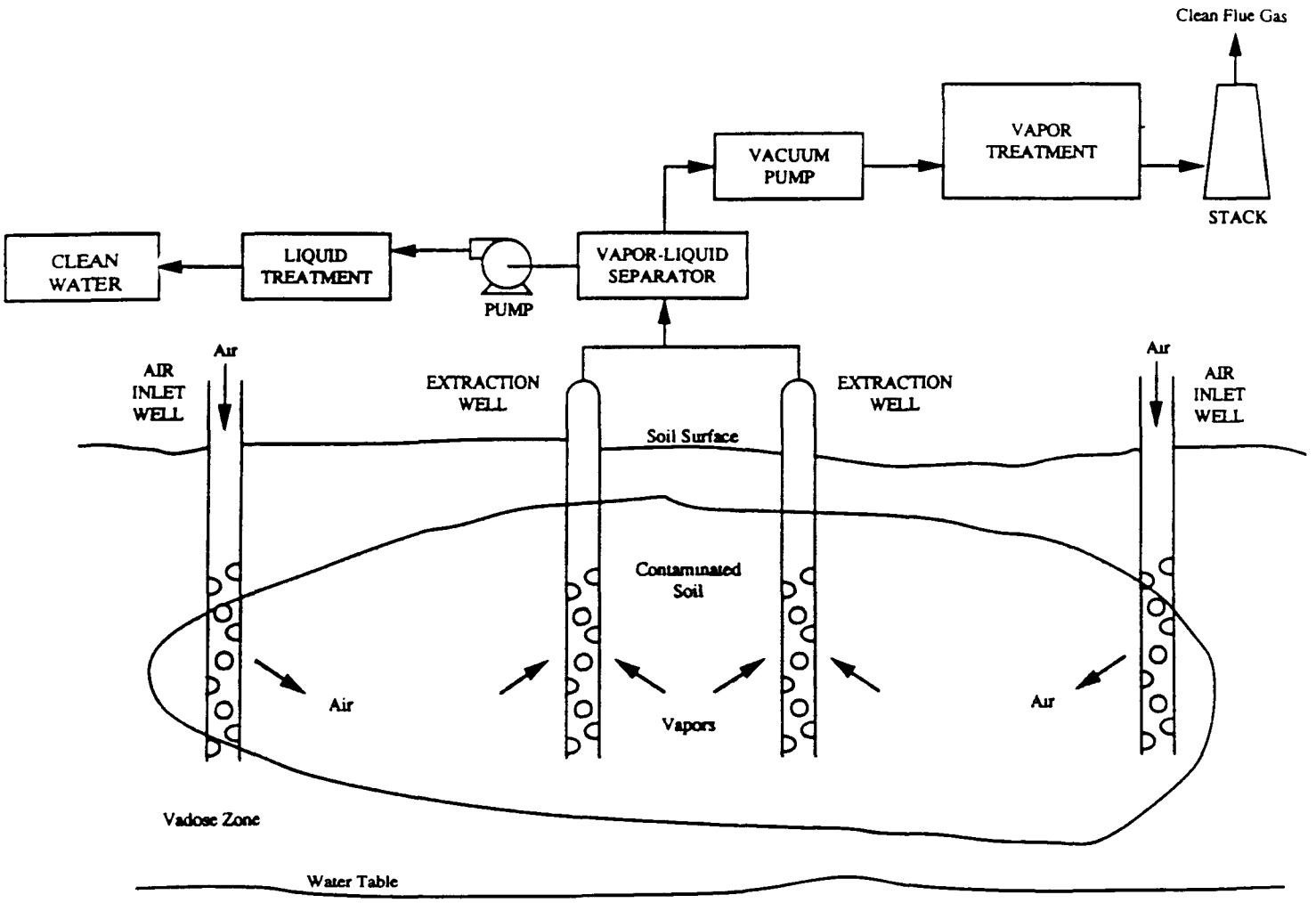

Figure 1. Generalized Process Flow Diagram for Soil Vapor Extraction.

An air/water separator is typically employed if water is pulled from the extraction wells. The separator serves to protect the air blowers or pumps and to increase the efficiency of any vapor treatment system that is used. The condensate from the separator may require treatment prior to discharge. For the large-scale remediations done at Superfund Sites, the air stream will normally require treatment to reduce its VOC content prior to discharge into the atmosphere. Carbon adsorption or catalytic oxidation are the most commonly used control technologies. Carbon adsorption systems may be present upstream or downstream of the vacuum pump. For SVE systems with small air flowrates (i.e., 30 to 100 scfm), internal combustion engines can also be used to control the air emissions.

ESTIMATION OF AIR EMISSIONS

There are several alternative approaches for estimating the emissions from a SVE system. The best method is to directly measure the emissions from the system while it is in full-scale or pilot-scale operation. The next best method is to estimate the emissions using predictive equations with site-specific inputs. If site-specific inputs are not available, a very conservative estimate can be made by using default values for the input parameters. Equations are given below for estimating long-term average and short-term emission rates.

Long-Term Average Emission Rate

A simple check of the total emissions potential for the site should also be made by dividing the total mass of a given contaminant to be removed from the soil by the expected duration of the clean-up:

$$ER = (S_V)(C_s)(\beta)(1)/\ t \qquad \text{(Eq. 1)}$$

where:
- ER = Average emission rate (g/sec);
- S_V = Volume of contaminated soil to be treated (m^3);
- C_s = Average contaminant concentration (ug/g);

ß = Bulk density of soil (g/cm^3);
1 = Constant ($g/10^6ug * 10^6cm^3/m^3$); and
t = Duration of remediation (sec).

Equation 1 assumes 100% recovery of the contamination at the site. The volume of contaminated soil and the total mass of each contaminant of concern are typically determined during the remedial investigation (RI) of the site, while the percent that can be recovered using SVE is typically determined during the feasibility study (FS) of the site. The duration of the clean-up will usually be limited by the rate at which contaminants can be cost-effectively extracted from the ground (see below). For Equation 1, a typical default value for bulk density of uncompacted soil is 1.5 g/cm^3. The following paragraphs discuss the key variables influencing air emissions from SVE systems and present an empirical equation for estimating a short-term emission rate.

Short-Term Emission Rate

The primary parameters affecting the emission rate of a given compound from a SVE system are: the concentration of the contaminant in the soil, the volatility of the contaminant (i.e. its vapor pressure), the soil permeability to air flow, and the vacuum well pressure. The soil permeability will depend on a number of factors including: air-filled porosity of the soil, the soil moisture content, the bulk soil temperature, the density and viscosity of the soil gas, and the presence of any macropores that result in channelized vapor flow. Due to the complex nature of subsurface vapor transport and the large variations in soil permeability to air flow at most sites, accurate prediction of SVE effectiveness and the resulting emissions based on models or equations derived from fundamental physical laws is not feasible. Instead, the flow rate of vapors through the soil is usually determined empirically and then used to estimate the emission rate.

The flow rate of vapors through the soil depends on the pressure gradient (which in turn is dependent on the soil permeability and the applied vacuum). The pressure gradient decreases with distance from the extraction well and a radius of

influence exists that defines the extent to which vapors can be drawn to the well. The length of this radius will vary from site to site and will dictate the number of wells required to remediate a site and their spacing. In practice, field tests are typically performed to assess the potential effectiveness of SVE for a given site. The field tests may be pilot-scale demonstrations of SVE or tests of soil-air permeability[2,3].

The results of the field tests can be used to estimate the emission rate (ER) in grams per second from the SVE system using Equation 2.

$$ER = (C_g)\left(\frac{Q}{60}\right)(10^{-6}) \qquad \text{(Eq. 2)}$$

where:

ER	=	Emission rate (g/sec);
C_g	=	Concentration in extracted vapors ($\mu g/m^3$);
Q	=	Vapor extraction rate (m^3/min);
1/60	=	Conversion factor (min/sec); and
10^{-6}	=	Conversion factor ($g/\mu g$).

The extraction rate, Q, can be estimated from the results of pilot-scale tests at the site if any changes in pump size and number of wells between the pilot- and full-scale systems are taken into account. If no pilot-scale data are available, results of field test of soil-air permeability can be used to estimate Q. If these too are not available, a default value can be used for the extraction rate. Typical flow rates for Q at Superfund sites range from 14 m^3/min (500 cfm) to 425 m^3/min (15,000 cfm), with a typical default value being Q = 85 m^3/min (3,000 cfm).

The contaminant concentration in the extracted vapors, C_g, can also be estimated from the results of pilot-scale tests at the site. The second best approach is to estimate C_g by collecting samples of the headspace vapors above the contaminated soil and measuring the concentration of the compound(s) of interest. These equilibrium soil-gas samples can be collected using ground (soil-gas) probes or by transferring soil samples from split-spoon samplers (to minimize VOC losses) to sealed containers and allowing the headspace to equilibrate.

Field data are required to get an accurate value for C_g. If no field data are available, however, a very conservative value for C_g can be estimated by assuming that the soil-gas is saturated. The maximum vapor concentration of any compound in the extracted vapors is its equilibrium or "saturated" vapor concentration, which is calculated from the compound's molecular weight, vapor pressure at the soil temperature, and the ideal gas law[3]:

$$C_g = \frac{(Pvap)(MW * 10^9)}{((R)(T))} \qquad \text{(Eq. 3)}$$

where:

C_g	=	Estimate of contaminant vapor concentration ($\mu g/m^3$);
Pvap	=	Pure component vapor pressure at the soil temperature (mm Hg);
MW	=	Molecular weight of component i (g/mole);
R	=	Gas constant = 62.4 L-mm Hg/mole -°K;
T	=	Absolute temperature of soil (°K); and
10^9	=	Conversion factor (μg-L/g-m^3).

Values of molecular weight, vapor pressure at 25°C, and saturated vapor concentration at 25°C are given in Appendix A. It is important to note that Equation 3 gives the theoretical maximum value of C_g. It will overpredict C_g for any compounds present in the soil at relatively low concentrations. Equation 3 will also overpredict the long-term average value of C_g since the concentration of contaminants in the gas extracted using a SVE system will tend to drop over time. It can drop by more than 95% in the first two days of operation[2], though pulsed operation will allow the soil-gas concentration to be periodically re-established at levels near the initial concentration.

Equation 3 assumes that an infinite source of vapors exists and that the contaminants are present in the soil or ground water at relatively high concentrations (e.g., total hydrocarbons of 500 ppm in the soil). Therefore, the vapor-phase concentration for a given compound is independent of the concentration of that same compound in the soil/liquid matrix.

Site-specific soil temperatures should be used if available. If not, annual average air temperatures can be used to estimate long-term values. Summer maximum air temperatures can be used to estimate short-term maximum values, if these are needed. A conservative default soil temperature is 298°K (25°C). Again, values for other inputs to Equation 3 can be found in Appendix A.

Emission control technologies used as part of the SVE system can generally be assumed to reduce emissions by 90 to 95%. The effect on emissions for any control device could be taken into account by adding the following term to Equation 2:

$$(1\text{-RE }(\%)/100)$$

where: RE = Removal efficiency of control device (%).

Published maximum short-term emission rates for soil vapor extraction systems are approximately 7 g/sec of total VOCs for systems without emission controls and approximately 0.35 g/sec for systems with emission controls[4].

ESTIMATION OF AMBIENT AIR CONCENTRATIONS

Estimates of short term ambient concentrations should be obtained by using site specific release parameters in the EPA's SCREEN model[5]. Estimates of long term concentrations should be obtained by using EPA's Industrial Source Complex (ISCLT) model. Here, for simplicity, the long term estimates are derived by multiplying the short term estimate obtained from the SCREEN model, by a conversion factor to obtain the annual average estimates. This approach results in a higher estimate of the annual average concentration than if the ISCLT model, with site specific data, is used.

Three air emission control options are typically employed for SVE systems: 1) no controls; 2) activated carbon control systems; and 3) catalytic oxidation control systems. Figure 2 was constructed using release parameters for the four different sizes of SVE systems with no air emission controls described in Table 1. The four scenarios

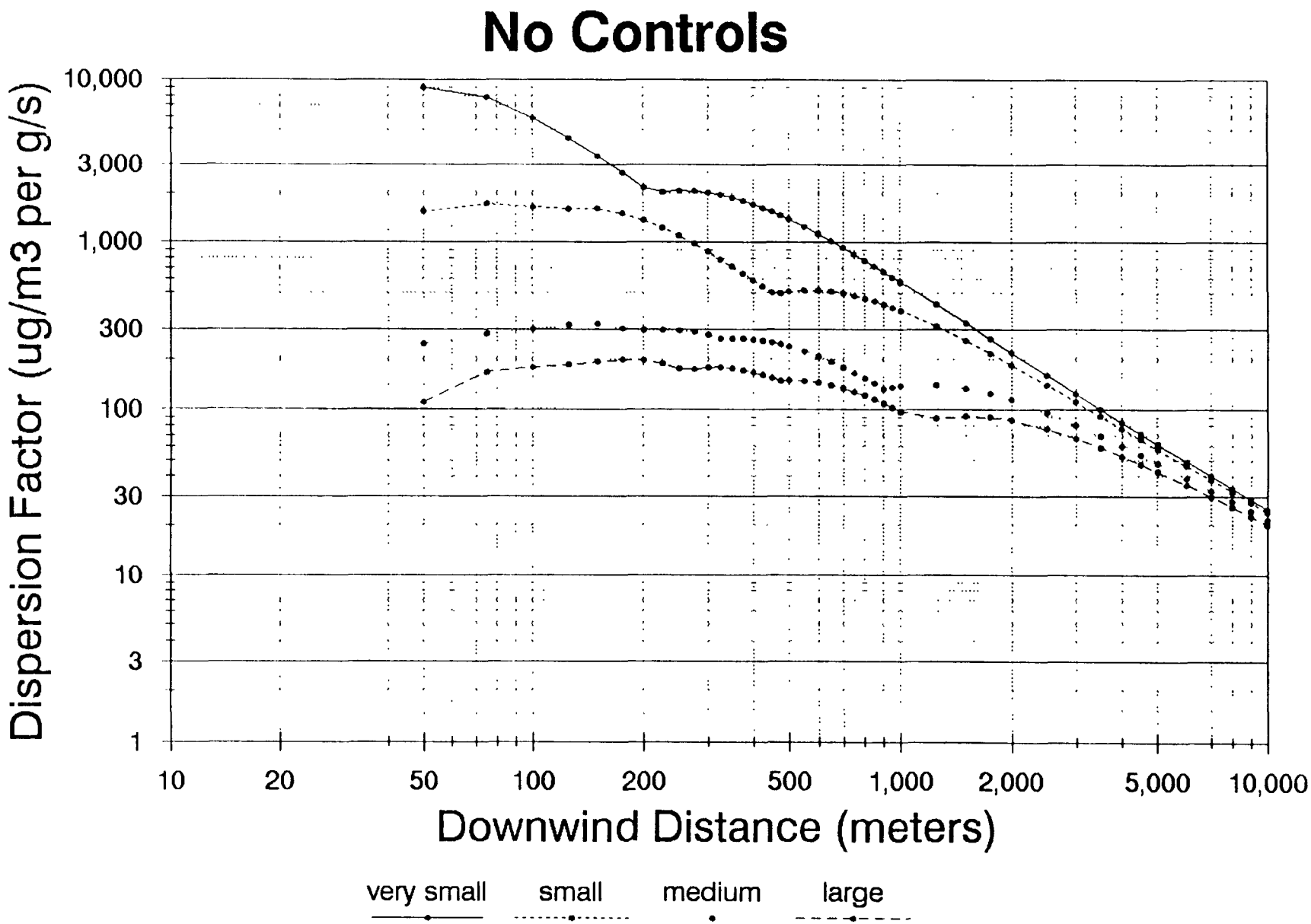

Figure 2. One-Hour Average Downwind Dispersion Factor Versus Distance for SVE System With No Air Emission Controls.

Table 1.

Example Scenarios for SVE with No Controls Based on Size of System

Parameter	Units	Scenario			
		Very Small	Small	Medium	Large
Exhaust Gas Flowrate	m^3/min cfm	1.4 50	14 500	85 3,000	425 15,000
Exhaust Gas Velocity	m/sec	3.0	7.4	12.5	14.2[a]
Exit Gas Temperature	°C	50	50	50	50
Stack Height	m	3.0	4.6	7.6	9.1
Stack Diameter	m	0.10	0.20	0.38	0.46

[a]Assume three adjacent stacks each handling 5,000 cfm. The flow is split to lower the velocity of the exiting gas to typical design levels to minimize corrosion of the stack.

listed in Table 1 vary in exhaust gas flowrate and in stack height and stack diameter (and in the resulting exhaust gas velocity). The scenarios were developed based on a review of the existing literature and discussions with researchers in the SVE area[6,7,8,9]. A flat terrain without any structures near the SVE system was assumed, and downwash was taken into account with the emitting stack being the only structure.

Figures 3 and 4 were constructed in an analogous manner to Figure 2 using the release parameters for SVE systems with activated carbon controls described in Table 2 and the release parameters for SVE systems with catalytic oxidation controls described in Table 3, respectively. As before, a flat terrain without any structures near the SVE system was assumed and downwash was taken into account with the emitting stack being the only structure.

All three control options assume the same system sizes, operating conditions, and stack height. The key variable is the exit gas temperature, which is dependent on the type of emission control device that is used. The exhaust gas flowrates for a given size of SVE system are the same for each of the control options once converted to standard cubic meters per minute (scmm). Figure 5 illustrates the effect of control type (i.e., exhaust gas temperature) on the dispersion factor by comparing a medium size SVE system with no controls, with activated carbon controls, and with catalytic oxidation controls.

The figures (2, 3, or 4) can be used to estimate the maximum hourly ambient air concentration for an emission rate of 1 gram per second at selected distances downwind from a SVE system with a given type of air emission control system. If the size of the system is not known, a medium size should be assumed. If the type of controls are not known, no controls should be assumed. The dispersion factor, in micrograms/m^3 per g/sec, obtained from the figures (2, 3, or 4) can be substituted into Equation 4 to estimate the maximum hourly ambient concentration and into Equation 5

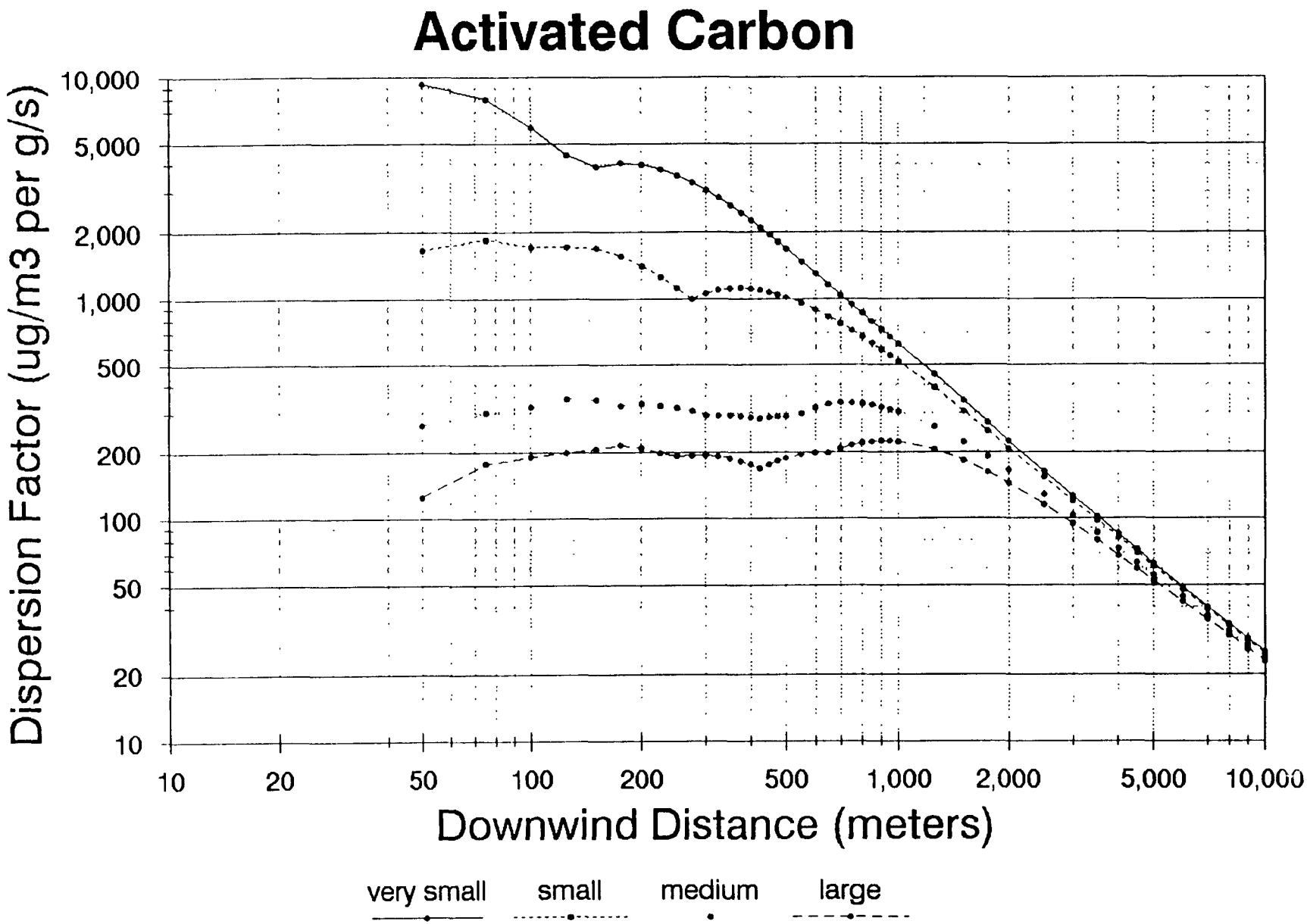

Figure 3. One-Hour Average Downwind Dispersion Factor Versus Distance for SVE System With Activated Carbon Controls.

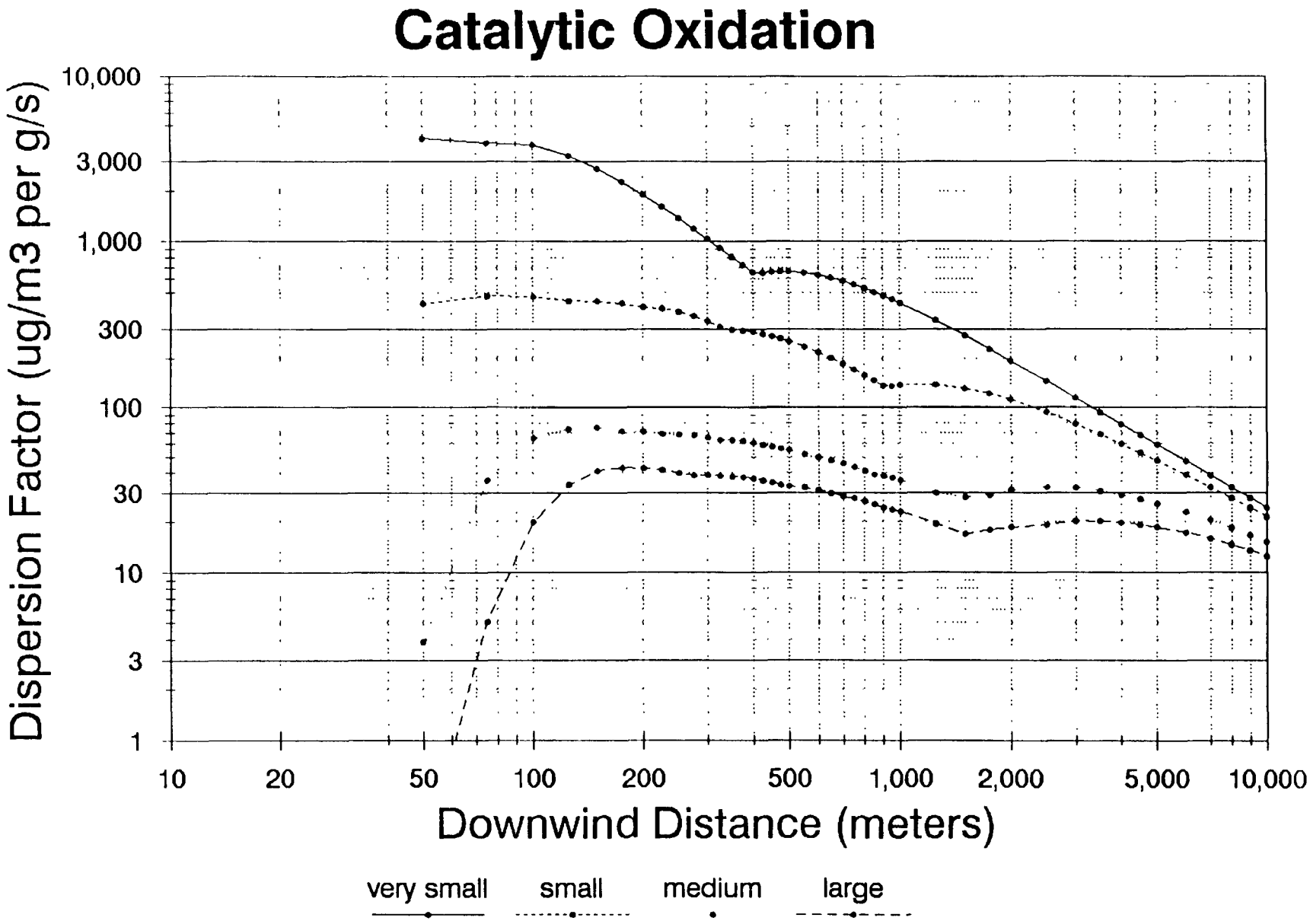

Figure 4. One-Hour Average Downwind Dispersion Factor Versus Distance for SVE System With Catalytic Oxidation Controls.

Table 2.

Example Scenarios for SVE with Activated Carbon Controls Based on Size of System

Parameter	Units	Scenario			
		Very Small	Small	Medium	Large
Exhaust Gas Flowrate	m^3/min cfm	1.3 46	13 461	78 2,770	392 13,800
Exhaust Gas Velocity	m/sec	2.8	6.9	11.5	13.1[a]
Exit Gas Temperature	°C	25	25	25	25
Stack Height	m	3.0	4.6	7.6	9.1
Stack Diameter	m	0.10	0.20	0.38	0.46

[a]Assume three adjacent stacks each handling 4,600 cfm. The flow is split to lower the velocity of the exiting gas to typical design levels to minimize corrosion of the stack.

Table 3.

Example Scenarios for SVE with Catalytic Oxidation Controls Based on Size of System

Parameter	Units	Scenario			
		Very Small	Small	Medium	Large
Exhaust Gas Flowrate	m^3/min cfm	2.6 92	26 918	156 5,510	780 27,500
Exhaust Gas Velocity	m/sec	5.5	13.8	22.9	26.1[a]
Exit Gas Temperature	°C	320	320	320	320
Stack Height	m	3.0	4.6	7.6	9.1
Stack Diameter	m	0.10	0.20	0.38	0.46

[a]Assume three adjacent stacks each handling 9,200 cfm. The flow is split to lower the velocity of the exiting gas to typical design levels to minimize corrosion of the stack.

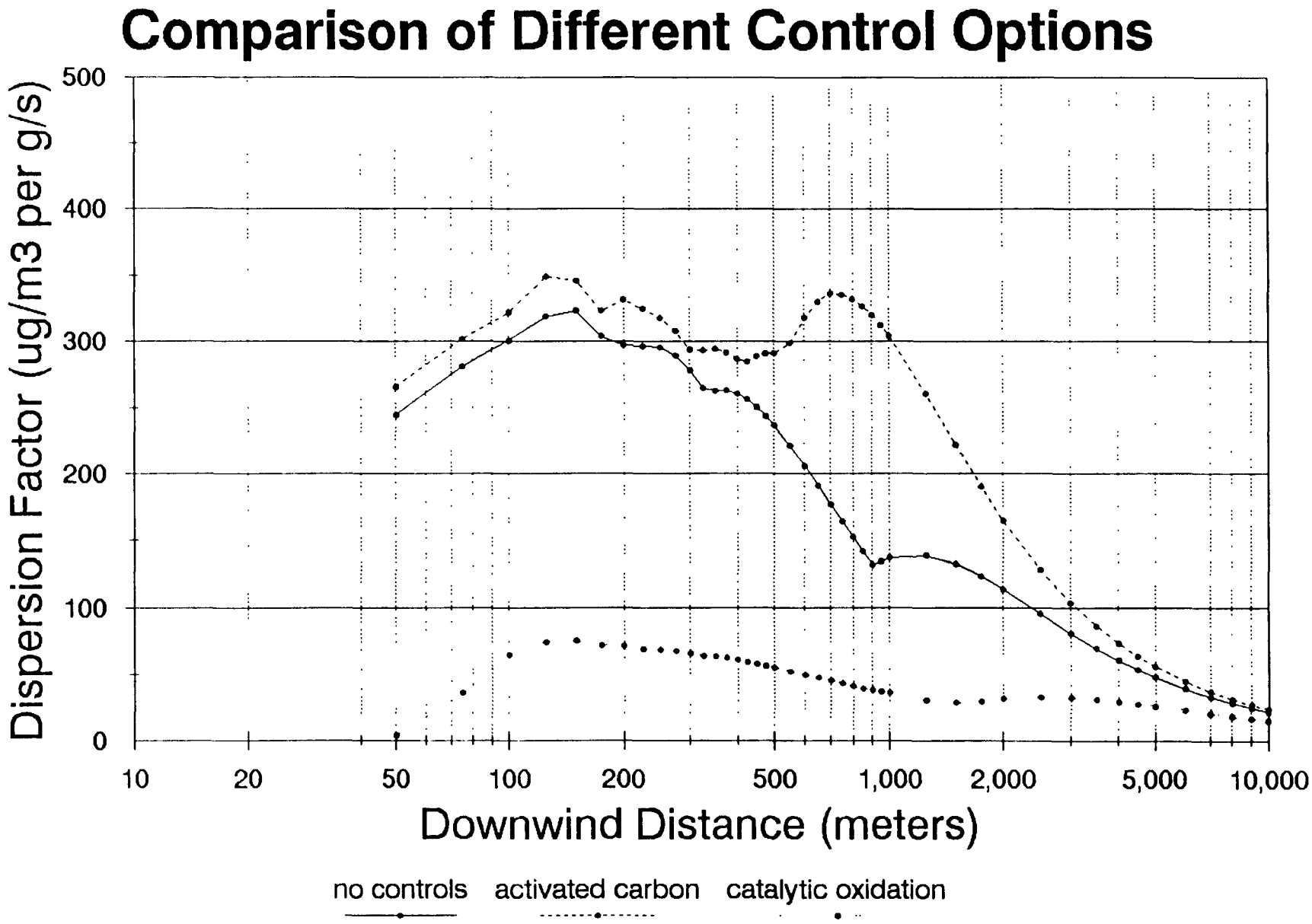

Figure 5. Comparison of One-Hour Average Downwind Dispersion Factor Versus Distance for SVE Systems With Various Control Options.

to estimate the annual average ambient air concentration for a given downwind distance. Since SCREEN provides maximum short-term estimates, the factor of 0.025 in Equation 4 is used to convert the short-term estimate to a maximum annual average estimate. A conservative factor of 0.025 assumes that the wind blows downwind 2.5% of the time over one year and that the terrain is relatively flat. This assumption is under review by EPA and is subject to change.

$$C_m = (ER)(F) \qquad \text{(Eq. 4)}$$

$$C_a = (ER)(F)(0.025) \qquad \text{(Eq. 5)}$$

where:

C_m	=	Maximum hourly ambient air concentration ($\mu g/m^3$);
C_a	=	Annual average ambient air concentration ($\mu g/m^3$);
ER	=	Emission rate (g/sec); and
F	=	Dispersion Factor from Figure 2, 3, or 4 ($\mu g/m^3/g/sec$).

ESTIMATION OF HEALTH EFFECTS

Cancer Effects Due to Long-Term Exposure

Potential cancer effects resulting from long-term exposure to substances emitted to the air can be evaluated using inhalation unit risk factors. Inhalation unit risk factors are a measure of the cancer risk for each $\mu g/m^3$ of concentration in the ambient air. They are available on EPA's Integrated Risk Information System (IRIS), the Agency's preferred source of toxicity information. User Support can be contacted at (513) 569-7254. Table 4 provides inhalation unit risk factors listed in IRIS as of January 1991 for selected organic compounds.

The next best source of inhalation unit risk factors is EPA's Health Effects Assessment Summary Tables (HEAST) which are updated quarterly.[10]

Equation 6 can be used to estimate the cancer risk at a specified distance downwind of the air stripper. Cancer risk is a measure of the increased probability of

Table 4.

Long-Term and Short-Term Health-Based Action Levels for Ambient Air

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogenicity	RfC-Based Concentrations for Non-Carcinogenic Effects ($\mu g/m^3$)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk $1/(\mu g/m^3)$	Inhalation RfC (mg/m^3)	10-6 70-year Risk ($\mu g/m^3$)		Lowest OEL/1000 ($\mu g/m^3$)	Lowest OEL/100 ($\mu g/m^3$)
1	Acetaldehyde	75-07-0	--	--	--	--	180	1,800
2	Acetic Acid	64-19-7	--	--	--	--	25	250
3	Acetic anhydride	108-24-7	--	--	--	--	20	200
4	Acetone	67-64-1	--	(4e-01)[b]	--	400	1,780	17,800
5	Acetonitrile	75-05-8	--	5e-02	--	50	67	670
6	Acrolein	107-02-8	ND[c,e]	1e-04[c]	--	0.1	0.23	2.30
7	Acrylic acid	79-10-7	--	3e-04	--	0.3	5.90	59
8	Acrylonitrile	107-13-1	6.8e-05	--	1.5e-02[c]	--	4.30	43
9	Allyl alcohol	107-18-6	--	(2e-02)[b]	--	20	4.80	48
10	Allyl chloride	107-05-1	ND[c,e]	1e-03	--	1	3.00	30
11	Aniline	62-53-3	(1.6e-06)[b]	--	6.3e-01	--	7.60	76
12	Anthracene	120-12-7	--	(1e+00)[b]	--	1,000	0.20	2.00
13	Benzaldehyde	100-52-7	--	(4e-01)[b]	--	400	--	--
14	Benzene	71-43-2	8.3e-06	--	1.2e-01[c]	--	0.30	3.00
15	Benzoic acid	65-85-0	--	(1e+01)[b]	--	10,000	--	--
16	Benzyl alcohol	100-51-6	--	(1e+00)[b]	--	1,000	--	--
17	Benzyl chloride	100-44-7	--	--	--	--	5	50
18	Bromoform	75-25-2	1.1e-06[c]	(7e-02)[b]	9.1e-01	70	5	50
19	1,3-Butadiene	106-99-0	2.8e-04	--	3.6e-03	--	22	220
20	n-Butane	106-97-8	--	--	--	--	1,900	19,000
21	2-Butanol	15892-23-6	--	--	--	--	303	3,030
22	n-Butanol	71-36-3	--	(4e-01)[b]	--	400	152	1,520
23	n-Butyl-Acetate	123-86-4	--	--	--	--	710	7,100
24	Tert-Butyl-Alcohol	75-65-0	--	--	--	--	300	3,000
25	Carbon disulfide	75-15-0	--	1e-02	--	10	12	120

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogencity	RfC-Based Concentrations for Non-Carcinogenic Effects ($\mu g/m^3$)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk $1/(\mu g/m^3)$	Inhalation RfC (mg/m^3)	10-6 70-year Risk ($\mu g/m^3$)		Lowest OEL/1000 ($\mu g/m^3$)	Lowest OEL/100 ($\mu g/m^3$)
26	Carbon Tetrachloride	56-23-5	1.5e-05	(2e-03)[b]	6.7e-02	2	12.60	126
27	Carbonyl Sulfide	463-58-1	--	--	--	--	--	--
28	Catechol	120-80-9	--	--	--	--	20	200
29	Chlorine	7782-50-5	--	--	--	--	1.5	15
30	Chlorobenzene	108-90-7	--	2e-02	--	20	46	460
31	Chlorodifluoromethane	75-45-6	--	--	--	--	3,540	35,400
32	Chloroform	67-66-3	2.3e-05	(4e-02)[b]	4.3e-02[c]	40	9.78	98
33	Chloromethyl methyl ether	107-30-2	ND	--	--	--	--	--
34	Chloropentafluoroethane	76-15-3	--	--	--	--	6,320	63,200
35	Chloroprene	126-94-8	--	1e-03[c]	--	1	35	350
36	m-Cresol	108-39-4	ND[e]	(2e-01)[b]	--	200	22	220
37	o-Cresol	95-48-7	ND[e]	(2e-01)[b]	--	200	22	220
38	p-Cresol	106-44-5	ND[e]	(2e-01)[b]	--	200	22	220
39	Cyanogen	460-19-5	--	(1e-01)[b]	--	100	20	200
40	Cyclohexane	110-82-7	--	--	--	--	1,030	10,300
41	Cyclohexanol	108-93-0	--	--	--	--	200	2,000
42	Cyclohexanone	108-94-1	--	--	--	--	100	1,000
43	Cyclohexene	110-83-8	--	--	--	--	1,010	10,100
44	Cyclopentane	287-92-3	--	--	--	--	1,720	17,200
45	Diazomethane	334-88-3	--	--	--	--	0.34	3.4
46	Dibutyl-O-Phthalate	84-74-2	--	(4e-01)[b]	--	400	5.00	50
47	o-Dichlorobenzene	95-50-1	--	2e-01	--	200	300	3,000
48	p-Dichlorobenzene	106-46-7	(6.9e-06)[b]	7e-01[c]	1.4e-01	700	450	4,500
49	Dichloroethylether	111-44-4	3.3e-04[c]	--	3.0e-03	--	29	290
50	Dichlorodifluoromethane	75-71-8	--	2e-01	--	200	4,950	49,500

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogenicity	RfC-Based Concentrations for Non-Carcinogenic Effects ($\mu g/m^3$)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk $1/(\mu g/m^3)$	Inhalation RfC (mg/m^3)	10-6 70-year Risk ($\mu g/m^3$)		Lowest OEL/1000 ($\mu g/m^3$)	Lowest OEL/100 ($\mu g/m^3$)
51	1,1-Dichloroethane	75-34-3	ND[e]	5e-01	--	500	400	4,000
52	1,2-Dichloroethane	107-06-2	2 6e-05	--	3.8e-02[c]	--	4.00	40
53	1,1-Dichloroethylene	75-35-4	5e-05	(3e-02)[b]	2.0e-02	30	4.00	40
54	cis-1,2-dichloroethylene	156-59-2	--	(4e-02)[b]	--	40	790	7,900
55	trans-1,2-dichloroethylene	156-60-5	--	(7-02)[b]	--	70	790	7,900
56	Dichloromethane	75-09-2	4.7e-07	3e+00[c]	2.1e-00	3,000	174	1,740
57	Dichloromonofluoromethane	75-43-4	--	--	--	--	40	400
58	1,2-Dichloropropane	78-87-5	(1.9e-05)[b]	--	5.3e-02	--	347	3,470
59	1,3-Dichloropropene	542-75-6	3.7e-05[c]	2e-02[c]	2.7e-02	20	4.5	45
60	1,2-Dichloro-1,1,2,2-Tetrafluoroethane	76-14-2	--	--	--	--	6,990	69,900
61	Diethanolamine	111-42-2	--	--	--	--	13	130
62	Diethyl amine	109-89-7	--	--	--	--	30	300
63	N,N-Dimethylaniline	121-69-7	--	--	--	--	25	250
64	Diethyl ether	60-29-7	--	--	--	--	1,200	12,000
65	Dimethylamine	124-40-3	--	--	--	--	18	180
66	Dimethyl formamide	68-12-2	--	3e-02	--	30	30	300
67	1,1-Dimethyl hydrazine	57-14-7	(2.5e-03)[b]	--	4.0e-04	--	1	10
68	2,4-Dinitrophenol	51-28-5	--	(7e-03)[b]	--	7	--	--
69	1,4-Dioxane	123-91-1	(3.1e-06)[b]	--	3.2e-01	--	90	900
70	Diphenyl	92-52-4	--	--	--	--	1.00	10
71	Epichlorohydrin	106-89-8	1.2e-06[c]	3e-04[c]	8.3e-01	0.3	7.6	76
72	1,2-Epoxybutane	106-88-7	--	--	--	--	--	--
73	Ethanol	64-17-5	--	--	--	--	1,880	18,800
74	Ethyl acetate	141-78-6	--	(3.0e+00)[b]	--	3,000	1,400	14,000
75	Ethyl acrylate	140-88-5	(1.4e-05)[b]	--	7.1e-02	--	20	200

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogencity	RfC-Based Concentrations for Non-Carcinogenic Effects ($\mu g/m^3$)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk $1/(\mu g/m^3)$	Inhalation RfC (mg/m^3)	10-6 70-year Risk ($\mu g/m^3$)		Lowest OEL/1000 ($\mu g/m^3$)	Lowest OEL/100 ($\mu g/m^3$)
76	Ethyl amine	75-04-7	--	--	--	--	18	180
77	Ethylbenzene	100-41-4	--	1e-00	--	1,000	434	4,340
78	Ethyl bromide	74-96-4	--	--	--	--	22	220
79	Ethyl carbamate	51-79-6	--	--	--	--	--	--
80	Ethyl chloride	75-00-3	--	1e+01	--	10,000	2,600	26,000
81	Ethylenediamine	107-15-3	--	(7.0e-02)[b]	--	70	25	250
82	Ethylene dibromide	106-93-4	2.2e-04[c]	--	4.5e-03	--	--	--
83	Ethylene glycol	107-21-1	--	(7.0e+00)[b]	--	7,000	125	1,250
84	Ethylene imine	151-56-4	--	--	--	--	0.88	8.80
85	Ethylene oxide	75-21-8	1.0e-04	--	1.0e-02	--	1.80	18
86	Formaldehyde	50-00-0	1.3e-05	--	7.7e-02	--	0.37	3.70
87	Formic Acid	64-18-6	--	(7e+00)	--	7,000	9.00	90
88	Furan	110-00-9	--	(4.0e-03)[b]	--	4	--	--
89	Glycerol	56-81-5	--	--	--	--	5.00	50
90	n-Heptane	142-82-5	--	--	--	--	1,600	16,000
91	n-Hexane	110-54-3	--	2e-01	--	200	176	1,760
92	Hydrazine	302-01-2	4.9e-03[c]	--	2.0e-04	--	0.13	1 3
93	Hydrochloric acid	7647-01-0	--	--	--	--	7.5	75
94	Hydrogen cyanide	74-90-8	--	--	--	--	11	110
95	Hydrogen Sulfide	7783-06-4	--	9e-04[c]	--	0.9	14	140
96	Isobutanol	78-83-1	--	1e+00	--	1,000	150	1,500
97	Isobutyl acetate	110-19-0	--	--	--	--	700	7,000
98	Isopropyl alcohol	67-63-0	--	--	--	--	980	9,800
99	Isopropyl amine	75-31-0	--	--	--	--	12	120
100	Isopropylbenzene	98-82-8	--	9e-03[c]	--	9	245	2,450

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogencity	RfC-Based Concentrations for Non-Carcinogenic Effects ($\mu g/m^3$)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk $1/(\mu g/m^3)$	Inhalation RfC (mg/m^3)	10-6 70-year Risk ($\mu g/m^3$)		Lowest OEL/1000 ($\mu g/m^3$)	Lowest OEL/100 ($\mu g/m^3$)
101	Methanol	67-56-1	--	(2e+00)[b]	--	2,000	260	2,600
102	Methyl acetate	79-20-9	--	(4e+00)[b]	--	4,000	606	6,060
103	Methyl acrylate	96-33-3	--	(1e-01)[b]	--	100	35	350
104	Methyl amine	74-89-5	-	--	--	--	12	120
105	Methyl bromide	74-83-9	--	(6e-03)[b]	--	6	19	190
106	Methyl-tert-butyl-ether	1634-04-4	--	--	--	--	--	--
107	Methyl chloride	74-87-3	1.8e-06	--	5.5e-01	--	103	1,030
108	Methylcyclohexane	108-87-2	--	--	--	--	1,600	16,000
109	Methyl-ethyl-ketone	78-93-3	ND	3e-01	--	300	590	5,900
110	Methyl formate	107-31-3	--	--	--	--	246	2,460
111	Methyl hydrazine	60-34-4	(3.1e-04)[b]	--	3.2e-03	--	0.019	0 19
112	Methyl iodide	74-88-4	--	--	--	--	10	100
113	Methyl-Isobutyl-Ketone	108-10-1	--	8e-02	--	80	205	2,050
114	Methyl isocyanate	624-83-9	--	--	--	--	0.047	0.47
115	Methyl-Isopropyl-Ketone	563-80-4	--	--	--	--	705	7,050
116	Methyl mercaptan	74-93-1	--	--	--	--	0.98	10
117	Methyl methacrylate	80-62-6	--	(3e-01)[b]	--	300	410	4,100
118	Methyl-n-Propyl-ketone	107-87-9	--	--	--	--	700	7,000
119	Alpha-methyl-styrene	98-83-9	--	(2e-01)[b]	--	200	240	2,400
120	Monoethanolamine	141-43-5	--	--	--	--	7.50	75
121	Morpholine	110-91-8	--	--	--	--	70	700
122	Naphthalene	91-20-3	--	(1e-02)[b]	--	10	50	500
123	2-Nitropropane	79-46-9	2.7e-03	2e-02[c]	3.7e-04	20	35	350
124	N-Nitrosodimethylamine	62-75-9	1.4e-02[c]	--	7.1e-05	--	--	--
125	N-Nitrosomorpholine	59-89-2	--	--	--	--	--	--

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogencity	RfC-Based Concentrations for Non-Carcinogenic Effects (µg/m^3)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk 1/(µg/m^3)	Inhalation RfC (mg/m^3)	10-6 70-year Risk (µg/m^3)		Lowest OEL/1000 (µg/m^3)	Lowest OEL/100 (µg/m^3)
126	n-Nonane	111-84-2	--	--	--	--	1,050	10,500
127	n-Octane	111-65-9	--	--	--	--	1,400	14,000
128	n-Pentane	109-66-0	--	--	--	--	1,770	17,700
129	Phenanthrene	85-01-9	--	--	--	--	0.20	2
130	Phenol	108-95-2	--	(2e+00)[b]	--	2,000	19	190
131	Phosgene	75-44-5	--	--	--	--	0.4	4
132	Phosphine	7803-51-2	--	3e-05	--	0.03	0.4	4
133	Phthalic anhydride	85-44-9	--	(7e+00)[b]	--	7,000	6.00	60
134	Propane	74-98-6	--	--	--	--	1,800	18,000
135	1,2-Propanediol	57-55-6	--	6e+00	--	6,000	--	--
136	1-Propanol	71-23-8	--	--	--	--	492	4,920
137	beta-Propiolactone	57-57-8	--	--	--	--	1.5	15
138	Propionaldehyde	123-38-7	--	--	--	--	--	--
139	Propionic acid	79-09-4	--	--	--	--	30	300
140	n-Propyl-Acetate	109-60-4	--	--	--	--	835	8,350
141	Propylene oxide	75-56-9	3.7e-06	3e-02	2.7e-01	30	48	480
142	1,2-Propylenimine	75-55-8	--	--	--	--	5	50
143	Pyridine	110-86-1	--	4e-03	--	4	15	150
144	Quinone	106-51-4	--	--	--	--	0.4	4
145	Styrene	100-42-5	5.7e-07	(7e-01)[b]	1.8e+00	700	213	2,130
146	1,1,1,2-Tetrachloro-2,2-Difluoroethane	76-11-9	--	--	--	--	4,170	41,700
147	1,1,2,2-Tetrachloroethane	79-34-5	5.8e-05	--	1.7e-02	--	6.90	69
148	Tetrachloroethylene	127-18-4	5.2e-07	(4e-02)[b]	1.9e+00	40	170	1,700
149	Tetrahydrofuran	109-99-9	--	--	--	--	590	5,900
150	Toluene	108-88-3	--	2e+00[c]	--	2,000	375	3,750

Table 4.
(Continued)

No.	Chemical	CAS Number	Carcinogenicity[a]	Chronic Toxicity[a]	Long-Term Action Levels			Short-Term Action Levels[d]
					Risk-Specific Concentrations for Carcinogencity	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m³)	Concentrations Based on Occupational Exposure[d]	
			Inhalation Unit Risk 1/(μg/m³)	Inhalation RfC (mg/m³)	10-6 70-year Risk (μg/m³)		Lowest OEL/1000 (μg/m³)	Lowest OEL/100 (μg/m³)
151	p-Toluidine	106-49-0	(5.4e-05)[b]	--	1.9e-02	--	8.80	88
152	1,1,1-Trichloroethane	71-55-6	--	1.0e+00	--	1,000	1,900	19,000
153	1,1,2-Trichloroethane	79-00-5	1.6e-05	(1.0e-02)[b]	6.3e-02	10	45	450
154	Trichloroethylene	79-01-6	1.7e-6	--	5.9e-01	--	269	2,690
155	Trichlorofluoromethane	75-69-4	--	7.0e-01	--	700	5,620	56,200
156	1,2,3-Trichloropropane	96-18-4	--	(2.0e-02)[b]	--	20	60	600
157	1,1,2-Trichloro-1,2,2-Trifluoroethane	76-13-1	--	(2.7e+01)[b]	--	27,000	7,600	76,000
158	Triethylamine	121-44-8	--	--	--	--	40	400
159	Trifluorobromomethane	75-63-8	--	--	--	--	6,090	60,900
160	1,2,3-Trimethylbenzene	526-73-8	--	--	--	--	123	1,230
161	1,2,4-Trimethylbenzene	95-63-6	--	--	--	--	123	1,230
162	1,3,5-Trimethylbenzene	108-67-8	--	--	--	--	123	1,230
163	Vinyl acetate	108-05-4	--	2e-01	--	200	30	300
164	Vinyl bromide	593-60-2	3.2e-05	--	3.1e-02	--	20	200
165	Vinyl-chloride	75-01-4	8.4e-05	--	1.2e-02	--	2.60	26
166	m-Xylene	108-38-3	--	7.0e-01	--	700	434	4,340
167	o-Xylene	95-47-6	--	7.0e-01	--	700	434	4,340
168	p-Xylene	106-42-3	--	3.0e-01	--	300	434	4,340

INSTRUCTIONS ON USE:

Read short-term action level directly from last column. For the three columns of long-term action levels, use the 10-6 risk data, if available, then the RfC data; use the OEL/1000 if no other data exists.

[a] EPA does not necessarily endorse the use of oral slope factors or oral RfDs to derive inhalation values. These are intended to serve as screening levels only and do not represent EPA guidance.
[b] Derived based on oral slope factor (or oral RfD).
[c] Verified, available on IRIS or Workgroup concurrence on final database file, and IRIS input pending.
[d] EPA does not necessarily endorse the use of occupational exposure limits to derive short- and long-term action levels for ambient air. These are intended to serve as screening levels only and do not represent EPA guidance. Intended changes for OEL values are included, where applicable.
[e] EPA Class C or D carcinogen.

developing cancer in a lifetime as a result of the exposure in question. Equation 6 assumes continuous exposure (24 hours/day, 365 days/year for 70 years) to the estimated annual average concentration in air.

$$R = (C_a)(IUR) \qquad \text{(Eq. 6)}$$

R is the cancer risk from long-term exposure to a specific VOC in air, dimensionless; C_a is the annual average ambient concentration estimated from Equation 5, $\mu g/m^3$; IUR is the inhalation unit risk factor, $(\mu g/m^3)^{-1}$ obtained from Table 4.

If the source operates for less than 70 years, multiply C_a by x/70, where x is the expected operating time of the source in years before using Equation 6. If more than one VOC is present, the cancer risks for each VOC can be summed to derive the total cancer risk at a specified distance downwind of the source.

<u>Non-Cancer Effects Due to Long-Term Exposure</u>

Non-cancer effects can be evaluated by using chronic inhalation reference concentrations (RfCs). An inhalation RfC is the an estimate (with uncertainty spanning perhaps an order of magnitude) of continuous exposure to the human population that is likely to be without appreciable risk of deleterious effects during a lifetime. RfCs for a limited number of compounds are available in IRIS and HEAST.

If inhalation RfCs were not available from either IRIS or HEAST, then chronic oral reference dose (RfD) data (in mg/kg/day) were multiplied by 70 kg (average body weight of an adult), then divided by 20 m^3/day (average adult inhalation rate), and finally multiplied by 1000 $\mu g/mg$ to derive a value in $\mu g/m^3$.

Ambient air action levels based on extrapolated oral data should be used cautiously. Before extrapolating data an array of factors should be assessed on a compound by compound basis to determine the feasibility of route-to-route

extrapolations. Important factors include the absorption, distribution, metabolism and excretion of the compound; portal of entry effects; acute and chronic toxicities, and other information.

For compounds lacking RfC or RfD values, action levels were based on occupational exposure levels recommended by the Occupational Safety and Health Administration (OSHA)[11] and the American Conference of Governmental Industrial Hygienists (ACGIH)[12]. The action levels were estimated by using the lower of the OSHA Permissible Exposure Limit-Time Weighted Average (PEL-TWA) level (or ceiling value) or the ACGIH Threshold Limit Value - Time Weighted Average (TLV-TWA) level (or ceiling value). The lower value was divided by 1000 to compensate for differences between occupational and residential exposures.

Long-term ambient air action level concentrations for non-carcinogens based on RfCs, extrapolated RfDs and occupational exposure levels for 168 compounds are also listed in Table 4. The action levels are in units of $\mu g/m^3$ to facilitate comparison to the ambient air concentrations estimated from Equation 5.

Short-Term Exposure

The short term (one hour) action levels, in $\mu g/m^3$, are presented in the last column of Table 4. The listed values were obtained by dividing the lowest of (1) the OSHA PEL-TWA or (2) the ACGIH TLV-TWA (or ceiling limits if 8-hour averages are not available) by 100. Division by 100 accounts for variations in human sensitivity (occupational levels are designed to protect healthy adult workers) and for uncertainties in using occupational exposure levels to derive ambient air action levels.

The occupational exposure levels on which the short-term action levels are based are subject to change. To check the values in Table 4 (or to derive values for compounds not listed in Table 4), determine the current OSHA PEL-TWA values by

consulting 29 CFR Section 1910 and the most recent edition of the ACGIH publication entitled Threshold Limit Values and Biological Exposure Indices.

The short-term action levels listed in Table 4 can be compared directly with the estimated maximum hourly ambient air concentrations obtained by using Equation 2 and the appropriate figure (2, 3, or 4). Use of the short term action levels should consider that no EPA accepted method exists to determine the short-term concentrations of airborne chemicals acceptable for community exposure.

EXAMPLE

The following steps illustrate the use of the estimation procedures presented in this document. The goal is to estimate the maximum hourly and annual average ambient air concentrations at the nearest receptor to the SVE system and compare these values to the action level concentrations listed in Table 4.

Step 1 For this example, assume a site that has approximately 10,000 m^3 of soil contaminated with chloroform, 1,1,1-trichloroethane, and trichloroethylene at concentrations in the soil of 100, 10,000, and 1,000 ug/g, respectively. The volume of contaminated soil is not known with any certainty. The bulk density of the soil at the site averages about 1.5 g/cm^3. During pilot-scale tests the respective vapor-phase concentrations of chloroform, 1,1,1-trichloroethane, and trichloroethylene in the extracted air was 100,000, 10,000,000, and 500,000 ug/m^3 (all three compounds are present at below their saturated level given in Appendix A). The size of the SVE system to be installed has not yet been determined, nor has the need for air emission controls, so a medium size SVE system with an 85 m^3/min (3000 cfm) air extraction rate and no air emission controls is assumed. The system is expected to be in continual operation for 6 months (1.58×10^7 seconds). The nearest off-site downwind receptor is 400 meters away.

Step 2 Estimate the total emissions potential for the site. Using Equation 1 and assuming 100% of the contamination is to be removed, the maximum average emission rate of chloroform would be:

$$ER = \frac{(10{,}000)(100)(1.5)(1)\left(\frac{100}{100}\right)}{(1.58 \times 10^7)} = 0.095 \text{ g/sec}$$

The maximum average emission rate for 1,1,1-trichloroethane is 9.5 g/sec, and for trichloroethylene is 0.95 g/sec.

Step 3 Estimate the emission rate of each compound. The pilot-scale data are used as inputs to Equation 2 along with the assumed flowrate of 85 m^3/min. For chloroform, the emission rate would be:

$$ER = (100{,}000)(85/60)(10^{-6}) = 0.14 \text{ g/sec}$$

The emission rates for all three compounds are given in Table 5.

Step 4 Compare the estimated emission rates from Step 3 to those from Step 2. The comparison is:

Compound	Equation 1 Emission Rate (g/sec)	Equation 2 Emission Rate (g/sec)
Chloroform	0.095	0.14
1,1,1-Trichloroethane	9.5	14
Trichloroethylene	0.95	0.71

Given the uncertainty associated with the soil volume term used in Equation 1, the agreement between the values is considered to be excellent. The check indicates that the emission rates estimated by Equation 2 are reasonable.

Step 5 Estimate the downwind ambient air concentrations. From Figure 2, the maximum hourly dispersion factor at a distance of 400 meters is approximately 250 ug/m^3 per g/sec emission rate. This corresponds to an annual average dispersion factor of 6.25 ug/m^3 per g/s (250 x 0.025 = 6.25). The ambient air concentrations estimated from Equations 4 and 5 are presented in Table 5. Using Equation 4, the maximum hourly average ambient air concentration for chloroform would be:

$$C_m = (0.14)(250) = 35 \text{ ug/m}^3$$

Table 5.

Estimated Emission Rates and Ambient Air Concentrations

	Vapor-Phase Concentration For Example Problem ($\mu g/m^3$)	Emission Rate (g/s)	Ambient Concentrations ($\mu g/m^3$)	
			Maximum Hourly	Annual Average
Chloroform	100,000	0.14	35	0.88
1,1,1-Trichloroethane	10,000,000	14	3,500	88
Trichloroethylene	500,000	0.71	180	4.4

Table 6.

Action Level Concentrations

	Table 4 Action Levels $\mu g/m^3$	
	Short-Term	Long-Term
Chloroform	98	0.043[1]
1,1,1-Trichloroethane	19,000	1,000[2]
Trichloroethylene	2,690	0.59[1]

[1]Based on 10^{-6}, 70-year risk.
[2]Based on reference dose concentrations (RfCs).

Using Equation 5, the annual average ambient air concentration for chloroform would be:

$$C_a = (0.14)(6.25) = 0.88 \text{ ug/m}^3$$

Step 6 Compare the downwind concentrations to the action level ambient air concentrations. The short-term and long-term action levels from Table 4 for the compounds of interest are presented in Table 6. None of the estimated maximum hourly ambient concentrations exceed the applicable action levels. The annual average ambient concentrations, however, exceed the long-term action levels for both chloroform and trichloroethylene, by a factor of 20 and 10 respectively.

Step 7 Document the results of the air pathway analysis and define a future course of action. Based on these screening level results, a more rigorous analysis of the air impacts is warranted. This would most likely involve refining the emission rate, dispersion, and health risk estimates. The emission rate estimate could be improved by using the actual or proposed operating conditions (e.g. exhaust gas rate) or by making field measurements at the SVE system. The dispersion estimates could be improved by using a less conservative model (e.g. EPA's Industrial Source Complex model) and site-specific meteorological conditions. The health risk estimate could be improved by using the expected operational lifetime of the SVE system rather than assuming a 70-year exposure. If the more rigorous analysis still indicates that adverse air impacts may occur, then the addition of air emission controls or altering the operating conditions to control emissions (e.g. exhaust gas rate or hours of operation per day) should be considered.

CONCLUSIONS

The procedures presented here are not intended to negate the need for rigorous analyses that consider site specific meteorological conditions and the health effects of the specific compounds involved. Although the procedures are based on what is typical and reasonable for cleaning up Superfund sites, the underlying assumptions need to be kept in mind. Emission models assume steady-state conditions, dispersion models assume Gaussian distribution of the plume contaminant concentration, and many of the health levels are not endorsed by the Environmental Protection Agency. EPA's Regional Toxicologist should be contacted for general toxicological information and technical guidance on evaluation of chemicals without established toxicity values.

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Jawad Touma and Norman Huey of EPA contributed to the overall direction of this project. The health effects sections were prepared in consultation with Fred Hauchman of EPA.

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APPENDIX A

PHYSICAL AND CHEMICAL CONSTANTS FOR SELECTED COMPOUNDS

APPENDIX A - PHYSICAL PROPERTY DATA

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)[1]	Saturated Vapor Conc. ($\mu g/m^3$)[1]
1	Acetaldehyde	75-07-0	C2H4O	44.00	760	1.80E+09
2	Acetic acid	64-19-7	C2H4O2	60.06	15.41	4.97E+07
3	Acetic anhydride	108-24-7	C4H6O3	102.09	5.266	2.89E+07
4	Acetone	67-64-1	C3H6O	58.08	266	8.30E+08
5	Acetonitrile	75-05-8	C2H3N	41.06	90	1.99E+08
6	Acrolein	107-02-8	C3H4O	56.1	244.2	7.36E+08
7	Acrylic acid	79-10-7	C3H4O2	72.1	5.2	2.02E+07
8	Acrylonitrile	107-13-1	C3H3N	53.06	114	3.25E+08
9	Allyl alcohol	107-18-6	C3H6O	58.08	23.3	7.27E+07
10	Allyl chloride	107-05-1	C3H5CL	76.53	368	1.51E+09
11	Aniline	62-53-3	C6H7N	93.13	1	5.01E+06
12	Anthracene	120-12-7	C14H10	178.23	1.3E-06	1.25E+01
13	Benzaldehyde	100-52-7	C7H6O	106.12	1	5.70E+06
14	Benzene	71-43-2	C6H6	78.12	95.2	4.00E+08
15	Benzoic acid	65-85-0	C7H6O2	122.12	0.00704	4.62E+04
16	Benzyl alcohol	100-51-6	C7H8O	108.14	0.15	8.72E+05
17	Benzyl chloride	100-44-7	C6H5CH2Cl	126.6	1.21	8.23E+06
18	Bromoform	75-25-2	CHBr3	252.77	5.6	7.61E+07
19	1,3-Butadiene	106-99-0	C4H6	54.09	2100.00	6.09E+09
20	N-Butane	106-97-8	C4H10	58.12	1820	5.69E+09
21	2-Butanol	15892-23-6	C4H10O	74.12	10	3.98E+07
22	N-Butanol	71-36-3	C4H10O	74.12	6.5	2.59E+07
23	N-Butyl-Acetate	123-86-4	C6H12O2	116.16	15	9.37E+07
24	Tert-Butyl-Alcohol	75-65-0	C4H10O	74.12	0.17	6.77E+05
25	Carbon disulfide	75-15-0	CS2	76.13	366	1.50E+09
26	Carbon tetrachloride	56-23-5	CCL4	153.82	113	9.34E+08
27	Carbonyl sulfide	463-58-1	COS	60.1	--	--
28	Catechol	120-80-9	C6H4(OH)2	110.1	--	--
29	Chlorine	7782-50-5	Cl2	70.9	--	--
30	Chlorobenzene	108-90-7	C6H5CL	112.56	11.8	7.14E+07
31	Chlorodifluoromethane	75-45-6	CHCLF2	86.47	--	--
32	Chloroform	67-66-3	CHCL3	119.38	208	1.33E+09
33	Chloromethyl methyl ether	107-30-2	C2H5Cl0	80.51	--	--
34	Chloropentafluoroethane	76-15-3	C2CLF5	154.47	--	--
35	Chloroprene	126-99-8	CH2CHCH2Cl	76.53	273	1.12E+09
36	M-Cresol	108-39-4	C7H8O	108.14	0.08	4.65E+05
37	O-Cresol	95-48-7	C7H8O	108.14	0.24	1.40E+06
38	P-Cresol	106-44-5	C7H8O	108.14	0.11	6.39E+05
39	Cyanogen	460-19-5	C2N2	52.04	3980	1.11E+10
40	Cyclohexane	110-82-7	C6H12	84.16	100	4.52E+08
41	Cyclohexanol	108-93-0	C6H12O	100.16	1.22	6.57E+06
42	Cyclohexanone	108-94-1	C6H10O	98.14	4.8	2.53E+07
43	Cyclohexene	110-83-8	C6H1O	82.15	--	--

Appendix A.
(Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)[1]	Saturated Vapor Conc. ($\mu g/m^3$)[1]
44	Cyclopentane	287-92-3	C5H10	70.13	317.44	1.20E+09
45	Diazomethane	334-88-3	CH2N2	42.04	–	–
46	Dibutyl-O-Phthalate	84-74-2	C16H22O4	278.35	1.00E-05	–
47	O-Dichlorobenzene	95-50-1	C6H4CL2	147.00	1	7.90E+06
48	P-Dichlorobenzene	106-46-7	C6H4CL2	147.00	1.2	9.48E+06
49	Dichloroethylether	111-44-4	C4H8Cl2O	143.02	1.4	[illegible]
50	Dichlorodifluoromethane	75-71-8	CCL2F2	120.91	4870	3.16E+10
51	1,1-Dichloroethane	75-34-3	C2H4CL2	98.96	234	1.24E+09
52	1,2-Dichloroethane	107-06-2	C2H4CL2	98.96	80	4.26E+08
53	1,1-Dichloroethylene	75-35-4	C2H2CL2	96.94	600	3.13E+09
54	cis-1,2-Dichloroethylene	156-59-2	C2H2CL2	96.94	208	1.08E+09
55	trans-1,2-Dichloroethylene	156-60-5	C2H2CL2	96.94	324	1.69E+09
56	Dichloromethane	75-09-2	CH2CL2	84.93	362	1.65E+09
57	Dichloromonofluoromethane	75-43-4	CHCL2F	102.92	1360	7.52E+09
58	1,2-Dichloropropane	78-87-5	C3H6CL2	112.99	42	2.55E+08
59	1,3-Dichloropropene	542-75-6	C3H4Cl2	110.98	43	2.57E+08
60	1,2-Dichloro-1,1,2,2-Tetrafluoroethane	76-14-2	C2CL2F4	170.92	–	–
61	Diethanolamine	111-42-2	C4H11NO2	105.14	–	–
62	Diethyl amine	109-89-7	C4H11N	73.14	350@35C	1.38E+09
63	N,N-Dimethylaniline	121-69-7	C8H11N	121.18	–	–
64	Diethyl ether	60-29-7	C4H10O	74.12	440@20C	1.75E+09
65	Dimethylamine	124-40-3	C2H7N	45.08	563 @ 0C	1.36E+09
66	Dimethyl formamide	68-12-2	C3H7NO	73.09	4.0	1.57E+07
67	1,1-Dimethyl hydrazine	57-14-7	C2H8N2	60.10	157	5.07E+08
68	2,4-Dinitrophenol	51-28-5	C6H4N2O5	184.11	53.8	5.32E+08
69	1,4-Dioxane	123-91-1	C4H8O2	88.11	37	1.75E+08
70	Diphenyl	92-52-4	C12H10	154.21	–	–
71	Epichlorohydrin	106-89-8	C3H5ClO	92.53	17	8.45E+07
72	1,2-Epoxybutane	106-88-7	C4H8O	72.0	–	–
73	Ethanol	64-17-5	C2H6O	46.07	50	1.24E+08
74	Ethyl acetate	141-78-6	C4H8O2	88.11	100	4.74E+08
75	Ethyl acrylate	140-88-5	C5H8O2	100.12	40	2.15E+08
76	Ethyl amine	75-04-7	C2H7N	45.08	1057	2.56E+09
77	Ethylbenzene	100-41-4	C8H10	106.16	10	5.71E+07
78	Ethyl Bromide	74-96-4	C2H5Br	108.97	–	–
79	Ethyl carbamate	51-79-6	C3H7NO2	89.09	10	4.79E+07
80	Ethyl Chloride	75-00-3	C2H5Cl	64.51	1200	4.16E+09
81	Ethylenediamine	107-15-3	C2H8N2	60.10	10.7	3.46E+07
82	Ethylene dibromide	106-93-4	C2H4Br	187.88	14	1.41E+08
83	Ethylene glycol	107-21-1	C2H6O2	62.07	0.13	4.34E+05
84	Ethylene imine	151-56-4	C2H5N	43.07	–	–

Appendix A.
(Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)[1]	Saturated Vapor Conc. ($\mu g/m^3$)[1]
85	Ethylene oxide	75-21-8	C2H4O	44.06	1250	2.96E+09
86	Formaldehyde	50-00-0	CH2O	30.03	3500	5.65E+09
87	Formic acid	64-18-6	CH2O2	46.03	42	1.04E+08
88	Furan	110-00-9	C4H4O	68.08	596	2.18E+09
89	Glycerol	56-81-5	C3H8O3	92.09	1.60E-04	7.92E+02
90	N-Heptane	142-82-5	C7H16	100.2	46	2.48E+08
91	N-Hexane	110-54-3	C6H14	86.18	150.3	6.96E+08
92	Hydrazine	302-01-2	H4N2	32.05	14.4	2.48E+07
93	Hydrochloric acid	7647-01-0	HCl	36.46	32,450	6.36E+10
94	Hydrogen cyanide	74-90-8	CHN	27.03	--	--
95	Hydrogen sulfide	7783-06-4	H2S	34.08	15,200	2.78E+10
96	Isobutanol	78-83-1	C4H10O	74.12	10	3.98E+07
97	Isobutyl acetate	110-19-0	C6H12O2	116.16	--	--
98	Isopropyl alcohol	67-63-0	C3H8O	60.1	42.8	1.38E+08
99	Isopropyl amine	75-31-0	C3H9N	59.11	460	1.46E+09
100	Isopropylbenzene	98-82-8	C9H12	120.19	10.9@40C	7.04E+07
101	Methanol	67-56-1	CH4O	32.04	114	1.96E+08
102	Methyl acetate	79-20-9	C3H6O2	74.08	235	9.36E+08
103	Methyl acrylate	96-33-3	C4H7O2	86.09	--	--
104	Methyl amine	74-89-5	CH5N	31.06	770@ -6C	1.29E+09
105	Methyl bromide	74-83-9	CH3BR	94.94	--	--
106	Methyl-tert-butyl-ether	1634-04-4	C5H12O	88.15	245	1.16E+09
107	Methyl chloride	74-87-3	CH3CL	50.49	3830	1.04E+10
108	Methylcyclohexane	108-87-2	C7H14	98.19	43	2.27E+08
109	Methyl-ethyl-ketone	78-93-3	C4H8O	72.11	100	3.88E+08
110	Methyl formate	107-31-3	C2H4O2	60.05	500	1.61E+09
111	Methyl hydrazine	60-34-4	CH6N2	46.07	49.6	1.23E+08
112	Methyl iodide	74-88-4	CH3I	141.94	91	--
113	Methyl-Isobutyl-Ketone	108-10-1	C6H12O	100.16	19.31	1.04E+08
114	Methyl isocyanate	624-83-9	C2H3NO	57.05	348	1.07E+09
115	Methyl-Isopropyl-Ketone	563-80-4	C5H10O	86.13	15.7	7.27E+07
116	Methyl mercaptan	74-93-1	CH4S	48.1	--	--
117	Methyl methacrylate	80-62-6	C5H8O2	100.10	39	2.10E+08
118	Methyl-N-Propyl-Ketone	107-87-9	C5H10O	86.13	--	--
119	Alpha-Methyl-Styrene	98-83-9	C9H10	118.18	0.076	4.83E+05
120	Monoethanolamine	141-43-5	C2H7NO	61.08	--	--
121	Morpholine	110-91-8	C4H9NO	87.12	10.08	4.72E+07
122	Naphthalene	91-20-3	C10H8	128.19	0.023	1.58E+05
123	2-Nitropropane	79-46-9	C3H7NO2	89.09	12.9	6.18E+07
124	N-Nitrosodimethylamine	62-75-9	C2H6N2O	74.08	--	--
125	N-Nitrosomorpholine	59-89-2	C4H8N2O	116.11	--	--

Appendix A.
(Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)[1]	Saturated Vapor Conc. ($\mu g/m^3$)[1]
126	N-Nonane	111-84-2	C9H20	128.26	4.28	2.95E+07
127	N-Octane	111-65-9	C8H18	114.23	17	1.04E+08
128	N-Pentane	109-66-0	C5H12	72.15	513	1.99E+09
129	Phenanthrene	85-01-8	C14H10	178.23	2.00E-04	1.92E+03
130	Phenol	108-95-2	C6H6O	94.11	0.0341	1.72E+05
131	Phosgene	75-44-5	CCl2O	98.92	1,394	7.41E+09
132	Phosphine	7803-51-2	H3P	34.00	2,000	3.66E+09
133	Phthalic anhydride	85-44-9	C8H4O3	148.11	0.0015	1.19E+04
134	Propane	74-98-6	C3H8	44.1	760	1.80E+09
135	1,2-Propanediol	57-55-6	C3H8O2	76.11	0.3	–
136	1-Propanol	71-23-8	C3H8O	60.1	20.85	6.74E+07
137	beta-Propiolactone	57-57-8	C3H4O2	72.06	3.4	1.32E+07
138	Propionaldehyde	123-38-7	C3H6O	58.08	300	9.37E+08
139	Propionic acid	79-09-4	C3H6O2	74.08	10	3.98E+07
140	N-Propyl-Acetate	109-60-4	C5H10O2	102.12	35	1.92E+08
141	Propylene oxide	75-56-9	C3H6O	58.08	524.5	1.64E+09
142	1,2-Propylenimine	75-55-8	C3H7N	54.1	112	3.26E+08
143	Pyridine	110-86-1	C5H5N	79.1	20	8.50E+07
144	Quinone	106-51-4	C6H4O2	108.09	–	–
145	Styrene	100-42-5	C8H8	104.15	7.3	4.09E+07
146	1,1,1,2-Tetrachloro-2,2-Difluoroethane	76-11-9	C2CL4F2	203.83	–	–
147	1,1,2,2,-Tetrachloroethane	79-34-5	C2H2CL4	167.85	6.5	5.86E+07
148	Tetrachloroethylene	127-18-4	C2CL4	165.83	19	1.69E+08
149	Tetrahydrofuran	109-99-9	C4H8O	72.11	72.1	2.79E+08
150	Toluene	108-88-3	C7H8	92.14	30	1.49E+08
151	P-Toluidine	106-49-0	C7H9N	107.16	0.3	1.73E+06
152	1,1,1-Trichloroethane	71-55-6	C2H3CL3	133.41	123	8.82E+08
153	1,1,2-Trichloroethane	79-00-5	C2H3CL3	133.41	25	1.79E+08
154	Trichloroethylene	79-01-6	C2HCL3	131.4	75	5.30E+08
155	Trichlorofluoromethane	75-69-4	CCL3F	137.37	667	4.92E+09
156	1,2,3-Trichloropropane	96-18-4	C3H5CL3	147.43	3.1	2.46E+07
157	1,1,2-Trichloro-1,2,2-Trifluoroethane	76-13-1	C2CL3F3	187.38	300	3.02E+09
158	Triethylamine	121-44-8	C6H15N	101.19	400	2.18E+09
159	Trifluorobromomethane	75-63-8	CBRF3	148.91	–	–
160	1,2,3-Trimethylbenzene	526-73-8	C9H12	120.19	–	–
161	1,2,4-Trimethylbenzene	95-63-6	C9H12	120.19	–	–
162	1,3,5-Trimethylbenzene	108-67-8	C9H12	120.19	1.86	1.20E+07
163	Vinyl Acetate	108-05-4	C4H6O2	86.09	115	5.32E+08
164	Vinyl bromide	593-60-2	C2H3Br	107.0	895	5.15E+09
165	Vinyl-Chloride	75-01-4	C2H3CL	62.5	2660	8.94E+09
166	M-Xylene	108-38-3	C8H10	106.2	8	4.57E+07

Appendix A.
(Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)[1]	Saturated Vapor Conc. ($\mu g/m^3$)[1]
167	O-Xylene	95-47-6	C8H10	106.2	7	4.00E+07
168	P-Xylene	106-42-3	C8H10	106.2	9.5	5.42E+07

[1] All vapor pressures are at 25° C unless otherwise indicated.