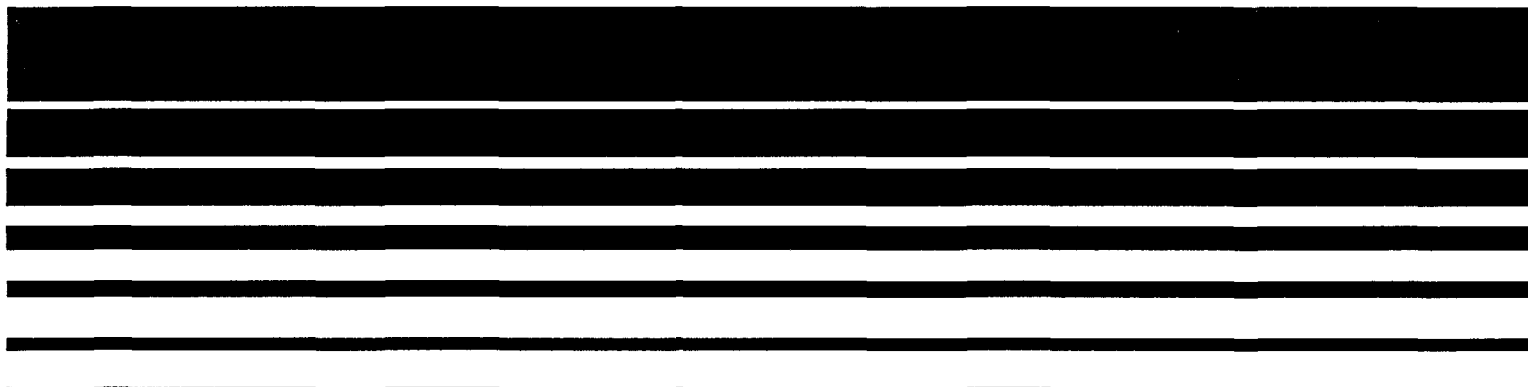




AIR/SUPERFUND NATIONAL TECHNICAL GUIDANCE STUDY SERIES

ESTIMATION OF AIR IMPACTS FOR BIOVENTING SYSTEMS USED AT SUPERFUND SITES



**ESTIMATION OF AIR IMPACTS
FOR BIOVENTING SYSTEMS
USED AT SUPERFUND SITES**

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
PROCESS DESCRIPTION	1
ESTIMATION OF VOC AIR EMISSIONS	6
Average Long-Term Uncontrolled VOC Emission Rate	6
Short-Term Uncontrolled VOC Emission Rate	7
ESTIMATION OF AMBIENT AIR CONCENTRATIONS	10
ESTIMATION OF HEALTH EFFECTS	15
Cancer Effects Due to Long-Term Exposure	15
Non-Cancer Effects Due to Long-Term Exposure	25
Short-Term Exposure	26
EXAMPLE	27
CONCLUSIONS	31
REFERENCES	31

APPENDIX A PHYSICAL PROPERTY DATA FOR SELECTED ORGANIC
 COMPOUNDS

APPENDIX B PHYSICAL PROPERTY DATA FOR SELECTED SEMI-VOLATILE
 ORGANIC COMPOUNDS

LIST OF TABLES

	<u>Page</u>
1	Default Values for VOC Emissions Model for Bioventing Systems 9
2	Example Scenarios for Bioventing Systems 12
3	Example Scenarios for an Area Source Bioventing Systems 12
4	Long-Term and Short-Term Health-Based Action Levels for Organic Compounds in Ambient Air 16
5	Long-Term and Short-Term Health-Based Action Levels for Selected Semi-Volatile Organic Compounds in Air 24
6	Estimated Emission Rates and Ambient Air Concentrations 30
7	Action Level Concentrations 30

LIST OF FIGURES

1	Bioventing System with Extraction Wells and an Exhaust Stack 3
2	Bioventing System without Extraction Wells 5
3	One-Hour Average Downwind Dispersion Factor Versus Distance for Bioventing Systems using an Extraction System 13
4	One-Hour Average Downwind Dispersion Factor Versus Distance for Bioventing Systems with Area Source Emissions 14

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 assessment of air impacts from various alternatives for cleaning up Superfund sites. Since these assessments 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 bioventing. These procedures are analogous to procedures for air strippers, soil vapor extraction systems, and excavation that have previously been published^{1,2,3}. Bioventing is an *in situ* remediation process where oxygen is introduced to the contaminated subsurface area to enhance biodegradation rates of the organic contaminants. Procedures are given to evaluate the effect of exhaust gas flow rate and contaminant concentration on the emission rates and on the ambient air concentrations at selected distances from the treatment area.

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 use could either under or over estimate the potential health effects. The use of action levels that are neither EPA-verified nor EPA-approved should be considered on a case-by-case basis. The statements and conclusions presented in this report are those of the authors and do not reflect U.S. EPA policy.

PROCESS DESCRIPTION

Bioventing is the process of supplying oxygen and other essential nutrients *in situ* to microorganisms in the subsurface to enhance biodegradation of organic contaminants in the soil. Bioventing is a combination of bioremediation and soil vapor extraction technology.

Like bioremediation, this treatment method relies on microorganisms to degrade the organic contaminants to water and carbon dioxide. These microbes are either indigenous to the site or are introduced into the contaminated area.

Figure 1 presents a general process diagram for bioventing systems with extraction wells and an exhaust stack. Bioventing is a developing technology, so there are many process configurations currently in use. Many bioventing systems utilize extraction wells to provide oxygen to the subsurface by applying a vacuum to the soil and thereby pulling ambient air through the unsaturated or vadose zone. In bioventing, as opposed to soil vapor extraction, the purpose of the extraction is not to volatilize and remove the contaminants but to provide an oxygen-enriched environment to enhance *in situ* biodegradation of the contaminants. Oxygen transfer can be enhanced with passive ambient air wells or with air injection wells which provide a positive pressure for oxygen transfer. The induced air flow, however, whether under positive or negative pressure, can cause the transfer (partitioning) of a significant amount of the more volatile compounds present in the soil to the gas phase. Extraction wells are typically positioned towards the perimeter of the contaminated area to increase transport time and thereby minimize volatilization of the organic contaminants (i.e., to give biodegradation more time to occur). Injection wells are typically put in the areas of highest concentration of contaminants to provide maximum oxygen transfer to these areas.

Bioventing systems are composed of the same type of equipment used in conventional soil vapor extraction (SVE) systems. The purpose of this equipment and the basis for this technology is quite different. SVE is used to collect contaminants in the subsurface by volatilization and removal. Bioventing systems operate under an entirely different principle: the induced air flow is used to create an oxygen-enriched environment to encourage bioremediation of the contaminants. For this reason, the total gas flow rates are significantly lower for bioventing systems than SVE systems. Typical flow rates for bioventing systems are 50 to 600 cfm^{4,5,6,7}; SVE systems have exhaust gas flow rates ranging from 500 to 15,000 cfm². The air flow rate for bioventing systems is dependent on the size of the site. Sites with larger volumes of soil to be treated will require a relatively larger amount of air flow to ensure adequate oxygen transfer to the soil.

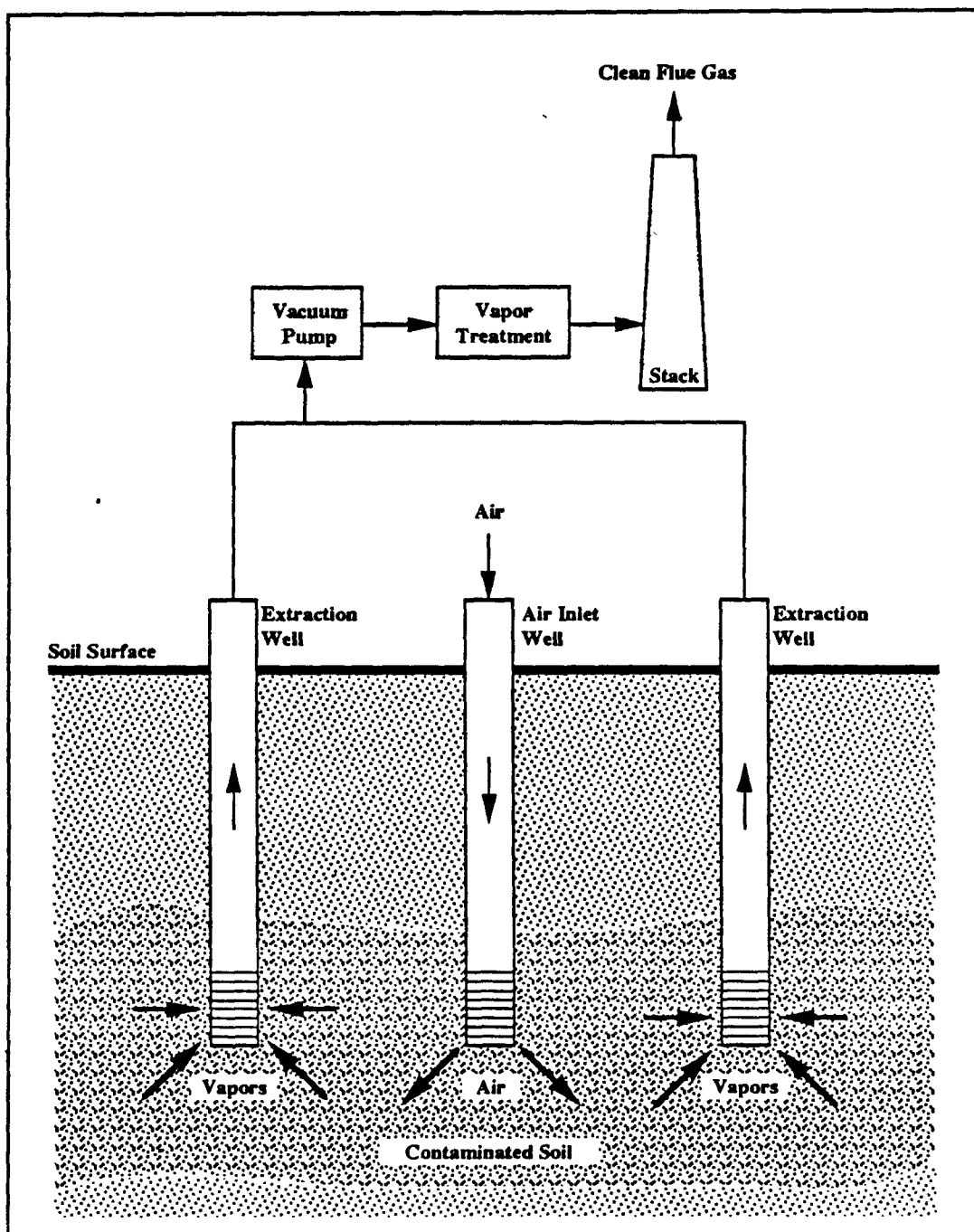


Figure 1. Bioventing System with Extraction Wells and an Exhaust Stack

In order to provide an environment suitable to the microorganisms, moisture and nutrients (nitrogen and phosphorus) are sometimes applied to the subsurface. This is usually achieved by applying the nutrients in an aqueous solution to the subsurface using drip irrigation hoses or to the soil surface above the contaminated area with water sprays. The addition of nutrients ensures that the biodegradation rate is limited only by the amount (concentration) of the organic contaminants present.

The specific point source of air emissions from bioventing systems is the off-gas collected by the vapor extraction system. The exhaust gas flow rate is small compared to soil vapor extraction (SVE) and other remediation processes. Also, the off-gas concentrations are lower than for SVE systems since biodegradation (destruction of the organic contaminants) is an integral part of the remediation process. Due to this, in many cases, the off-gas from the bioventing system is not treated. Collection and control equipment such as activated carbon or afterburners can be used to prevent the release of contaminants to the atmosphere. If control devices are present and working properly, the stack will vent small concentrations of the original VOC contaminants, as well as any products of combustion that might occur from the afterburner. The estimates of uncontrolled emissions obtained from this manual can be used to help estimate the required removal efficiency of an emission control system or the size and cost of a given control system.

When injection wells are used to supply oxygen and no gas extraction system is used, the injected air results in a positive pressure gradient in the soil, and the emissions are diffused over a wide area. An example of such a system is shown in Figure 2. Bioventing systems without extraction wells and an exhaust stack are less common than systems with these components. Similarly, area-wide emissions can occur with an extraction well system if it does not adequately collect the injected air. Typically, the air injection rates are low enough that emissions at the surface are thought to be minimal. Emissions from leaking components of the bioventing system and control devices are possible as well, but these emissions are usually considered to be negligible and are not considered in this document.

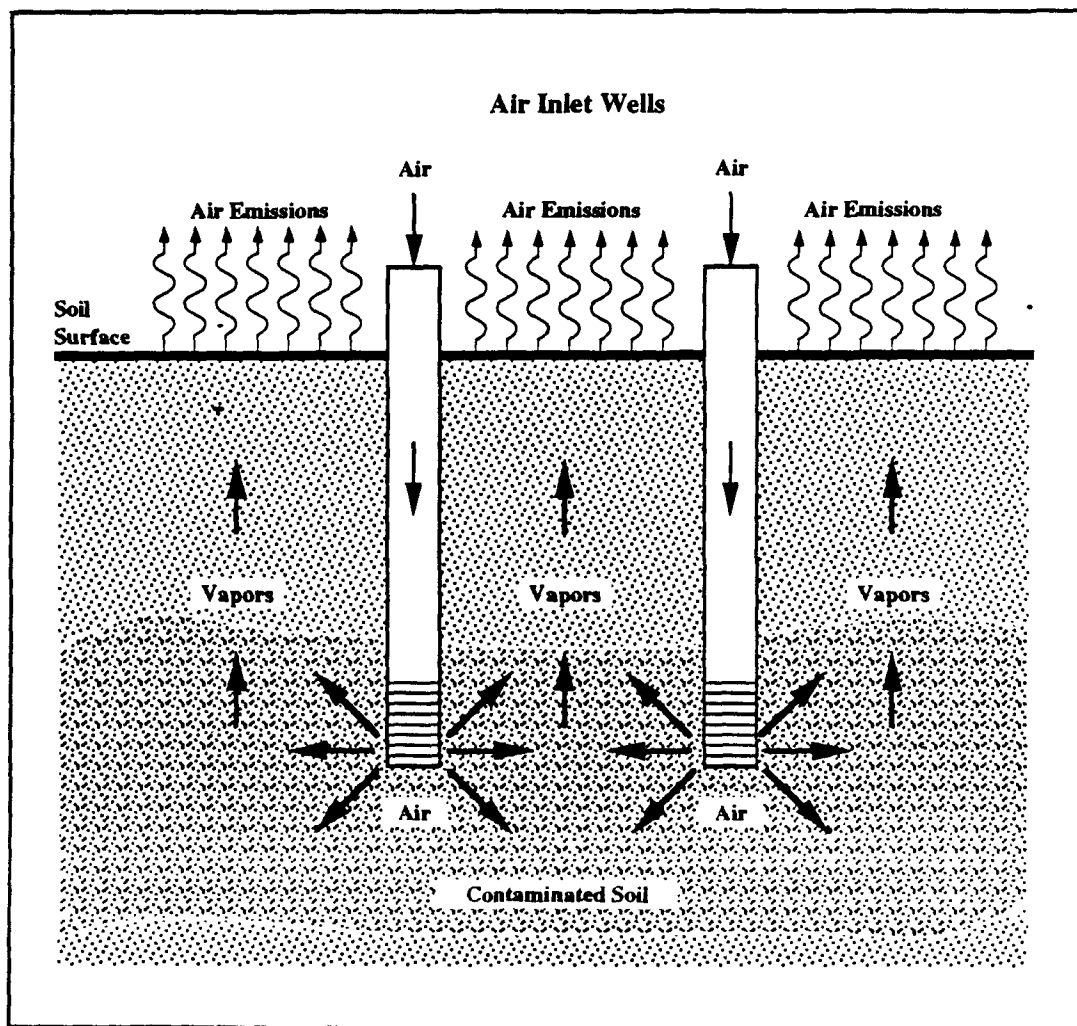


Figure 2. Bioventing System without Extraction Wells

ESTIMATION OF VOC AIR EMISSIONS

There are several alternative approaches for estimating the emissions from bioventing processes. The best method is to directly measure the emissions during full-scale or pilot-scale operations. The next best method is to estimate the emissions using predictive equations with site-specific inputs. If site-specific information is not available, a conservative estimate can be made using default values for the input parameters. Equations are given below for estimating an average long-term emission rate (Equation 1) and a short-term emission rate (Equation 2). Equation 2 is the recommended equation for estimating volatile organic compound (VOC) emissions; Equation 1 can be used as a gross check of total emissions.

Average Long-Term Uncontrolled VOC Emission Rate (Worst Case)

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

$$ER_{avg} = \frac{(S_v)(C)(\beta)(1)}{t_R} \quad (\text{Eq. 1})$$

where ER_{avg} = Average worst case emission rate (g/sec);
 S_v = Volume of contaminated soil to be treated (m^3);
 C = Average contaminant concentration ($\mu g/g$);
 β = Bulk density of soil (g/cm^3);
 1 = Constant ($g/10^6 \mu g * 10^6 cm^3/m^3$); and
 t_R = Duration of remediation (sec).

The volume of contaminated soil and the total mass of each contaminant of concern present typically are determined during the remedial investigation (RI) of the site, while the fraction of contaminated soil that must be treated typically is determined during the feasibility study (FS) for the site. Final clean-up criteria also should be considered when calculating the volume of soil to be treated since remediation to background levels is usually not required. The duration of the clean-up will be limited by the biodegradation rate of the less biodegradable contaminants. Biodegradation rates for various bioventing field programs have

been documented⁸. For Equation 1, a typical default value for bulk density of uncompacted soil is 1.5 g/cm³.

Equation 1 assumes that 100% of the organic contaminants present in the soil will eventually be volatilized. However, this may not be the case for all of the contaminants, especially semi-volatile organic compounds. This is apparent in one field study where up to 80% of the hydrocarbons were removed by biodegradation (versus 20% removed by volatilization) when the air flow rates were optimized to minimize the volatilization and maximize the biodegradation of the contaminants at the site^{4,6,7}.

Short-Term Uncontrolled VOC Emission Rate

The primary factors affecting the emission rate of a given compound from a bioventing system are the concentration of the contaminant in the soil and the volatility of the contaminant. Uncontrolled VOC emissions from a bioventing system can be estimated by using the following mass balance approach:

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

where ER = Emission rate for contaminant of interest (g/sec);
C_s = Concentration of the contaminant in the soil gas (μg/m³);
Q = Exhaust gas flow rate (m³/min);
1/60 = Conversion factor (min/sec); and
10⁻⁶ = Conversion factor (g/μg).

Equation 2 does not take into account emissions, if any, from the ground surface.

Site-specific field data must be collected (e.g., during the RI/FS) to provide the input data necessary to generate reasonably accurate estimates of air emissions. The minimum field data required are knowledge of the specific contaminants present in the soil to be treated and the average contaminant concentrations.

The preferred source of input data for Equation 2 is field measurements for the bioventing system configuration. The exhaust gas flow rate may be available from design specification documents. The properties of the contaminated soil, such as air-filled porosity, moisture content, and bulk temperature can affect the volume and composition of the collected off-gas. Field test data should be obtained to estimate these parameters when possible. Once the bioventing system is in operation, stack sampling of emissions from the system can be performed to confirm the emission estimates.

If the exhaust gas flow rate is not available from the sources listed above, it can be estimated from the following equation:

$$Q = \left(\frac{1.0}{1,440} \right) (S_v)(E_a) \quad (\text{Eq. 3})$$

where 1.0 = Estimated flow rate for maximum biodegradation and minimum volatilization (pore volume/day);
 1/1440 = Conversion factor (day/min); and
 E_a = Air-filled porosity (fraction).

Battelle has found that flow rates equivalent to 0.25 to 2.0 pore volumes per day are typical for bioventing systems [soil pore volume = $(S_v)(E_a)$]⁴. A flow rate of 1.0 pore volumes per day is thought to maximize the amount of biodegradation and minimize the amount of volatilization. Table 1 presents default values for air-filled porosity, if field data for this parameter are not available. If the soil type is not known, then a sandy silty soil type can be assumed.

The best values for the contaminant concentration in the off-gas, C_g , are field measurements from a pilot-scale system. The second best approach is to estimate C_g by analyzing the headspace vapors above the contaminated soil for the contaminants in the soil. If field data is not available, however, a very conservative estimate for C_g can be made by assuming that the soil-gas is saturated. The maximum vapor concentration of any compound in the collected vapor is its equilibrium or saturated vapor concentration⁹:

Table 1.

Default Values for VOC Emissions Model for Bioventing Systems

Parameter	Symbol	Units	Default Value	Expected Range	Reference
Exhaust Gas Flow Rate ^a	Q	m ³ /min	5.7	1.4 - 142	--
Air Filled Soil Porosity	E _a	Fraction			Author's estimate
Clayey Soil			0.28	0.22 - 0.34	
Silty Soil			0.31	0.25 - 0.37	
Sandy Soil			0.39	0.34 - 0.39	
Other Parameters of Possible Interest					
Equivalent Flow Rate	--	Pore volume/day	1.0	0.25 - 2.0	4

^aAssumes dry standard conditions (20°C, 1 atm)

(Eq. 4)

$$C_g = \frac{(P_{vap})(MW)(10^9)}{(R)(T)}$$

where P_{vap} = Pure contaminant vapor pressure at the soil temperature (mm Hg);
MW = Molecular weight of the contaminant (g/gmol);
R = Gas constant = 62.4 L-mm Hg/gmol-°K;
T = Absolute temperature of soil (°K); and
 10^9 = Conversion factor ($\mu\text{g-L/g-m}^3$).

Values of molecular weight and vapor pressure and saturated vapor concentration at 25°C for various contaminants are given in Appendices A and B. Equation 4 gives the theoretical maximum soil-gas concentration. This is an overprediction for compounds present in the soil at relatively low concentrations. Equation 4 will also overpredict the long-term average value of C_g since the soil-gas concentration tends to drop over time. Also, biodegradation is not accounted for in this model. In addition, if all other factors are constant, C_g will decrease as Q increases.

VOC control devices generally will reduce the emissions by one to two orders of magnitude. Equation 2 can be modified to account for the effectiveness of any control device by adding the following term:

$$(1 - CE/100)$$

where CE = Control efficiency (%).

More information on VOC control devices and their design, applicability, and cost is available in an EPA manual on controlling air emissions at Superfund sites.¹⁰

ESTIMATION OF AMBIENT AIR CONCENTRATIONS

Estimates of short-term, worst-case ambient concentrations should be obtained by using site specific release parameters in the EPA's TSCREEN model¹¹. Estimates of long-term concentrations should be obtained by using EPA's Industrial Source Complex (ISCLT) model. Here, for simplicity, the annual average estimates are derived by multiplying the short-term estimate obtained from the TSCREEN model, by a conversion

factor to account for variations of wind direction over time. This approach results in a higher estimate of the annual average concentration than if the ISCLT model, with site specific data, is used.

Typical remediation scenarios for bioventing systems that are point sources are given in Table 2. Table 3 presents the dimensions of a typical area source for a bioventing system where the vapors are not collected with an extraction system. The scenarios are based on information obtained from a review of the existing literature and conversations with vendors of bioventing systems. Figures 3 and 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 bioventing system with and without extraction wells. Of the variables listed in Table 2, the stack height and the exhaust gas velocity and temperature are used to estimate the downwind dispersion in Figure 3. For Figure 4, the surface area and release height are used to estimate the downwind concentrations. The dispersion model used is not reliable for estimating air concentrations close-in to area sources. Estimates should not be made for any downwind location that is closer to the source than the side length of the source (30 m in this case).

Figures 3 and 4 illustrate the uncontrolled downwind concentrations for the example bioventing systems. These curves were calculated according to the following assumptions: 1) the combined emission rate is 1 gram per second; 2) a flat terrain without any structures near the bioventing system; 3) the emission plume is of low, positive buoyancy; 4) the stack is the only downwash structure (Figure 3 only); and 5) the receptors are at ground level. For the area source, the emissions are assumed to be uniformly distributed over the emitting area and constant over time. The third-order inflection points in the curves are an artifact of the model. Ideally, the curves should follow a smooth decay from peak values.

If a given area source is larger than the example scenario, the curve in Figure 4 may still be used. The dispersion factor, in $\mu\text{g}/\text{m}^3$ per g/sec, obtained from Figure 3 or 4 can be substituted into Equation 5 to estimate the maximum hourly ambient concentration and into Equation 6 to estimate the annual average ambient air concentration for a given downwind distance.

Table 2.

Example Scenarios for Bioventing Systems

Parameter	Units	Typical System	Large Stack ^a System
Gas Volume ^b	m ³ /min cfm	5.7 200	5.7 200
Stack Height	m	4.6	4.6
Stack Diameter	m	0.1	0.5
Exit Gas Velocity ^b	m/sec	12.1	0.5
Exit Gas Temperature ^c	°C	25	25

^aRefers to a system with a larger stack diameter, i.e., 18 inches (0.5 m) compared to 4 inches (0.1 m).

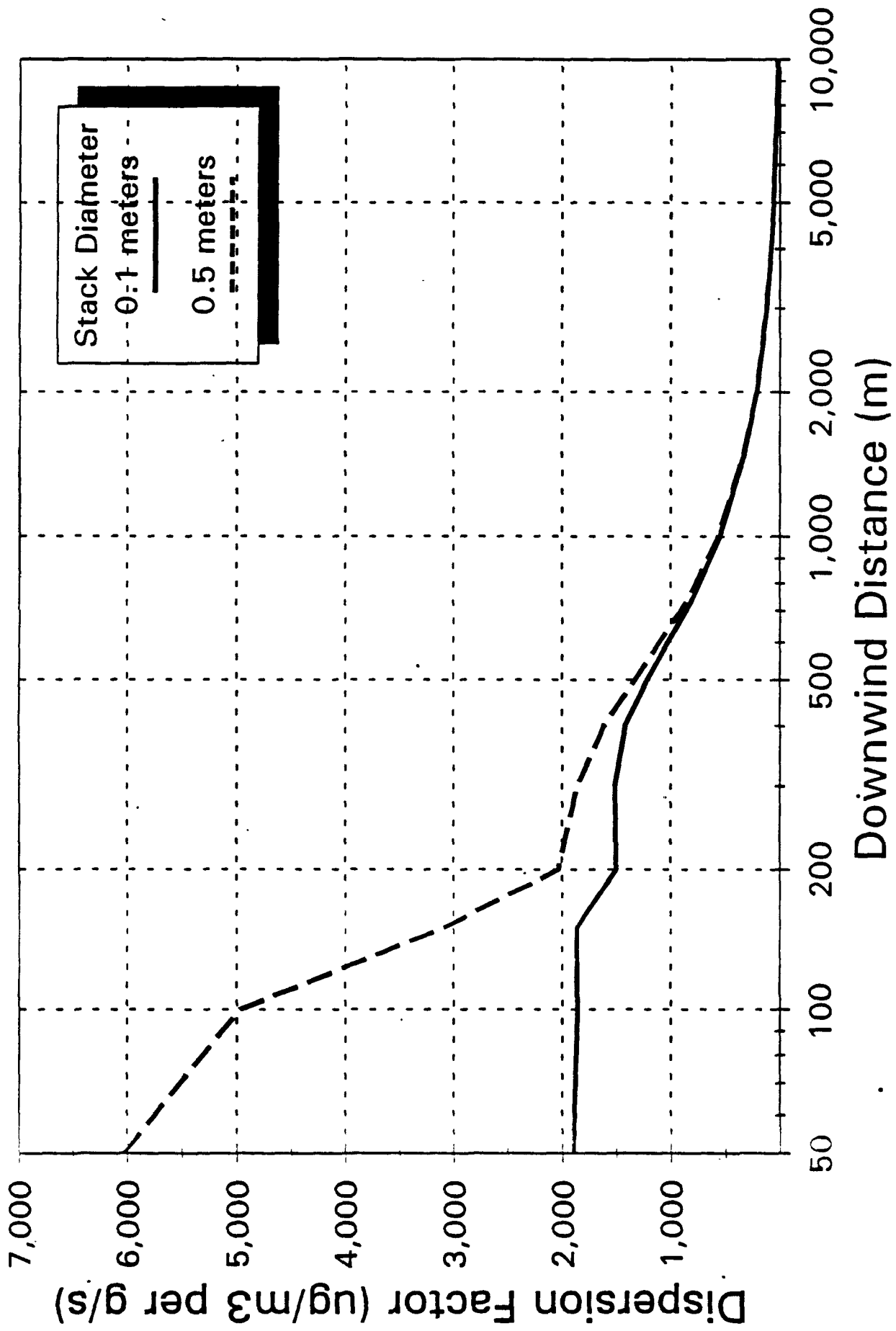
^b Assumes dry standard conditions (20°C, 1 atm).

^c Assumes either no off-gas treatment or treatment with activated carbon; if an afterburner is used to treat the off-gas, the temperature will be much higher.

Table 3.

Example Scenario for an Area Source Bioventing System

Parameter	Units	Scenario
Treatment Area:		
Dimensions	m	30 x 30
Area	m ²	900
Release Height	m	0



Exhaust gas temperature is 25C
Stack Height is 4.6 meters

Figure 3. One-Hour Average Downwind Dispersion Factor Versus Distance for Bioventing Systems using an Extraction System

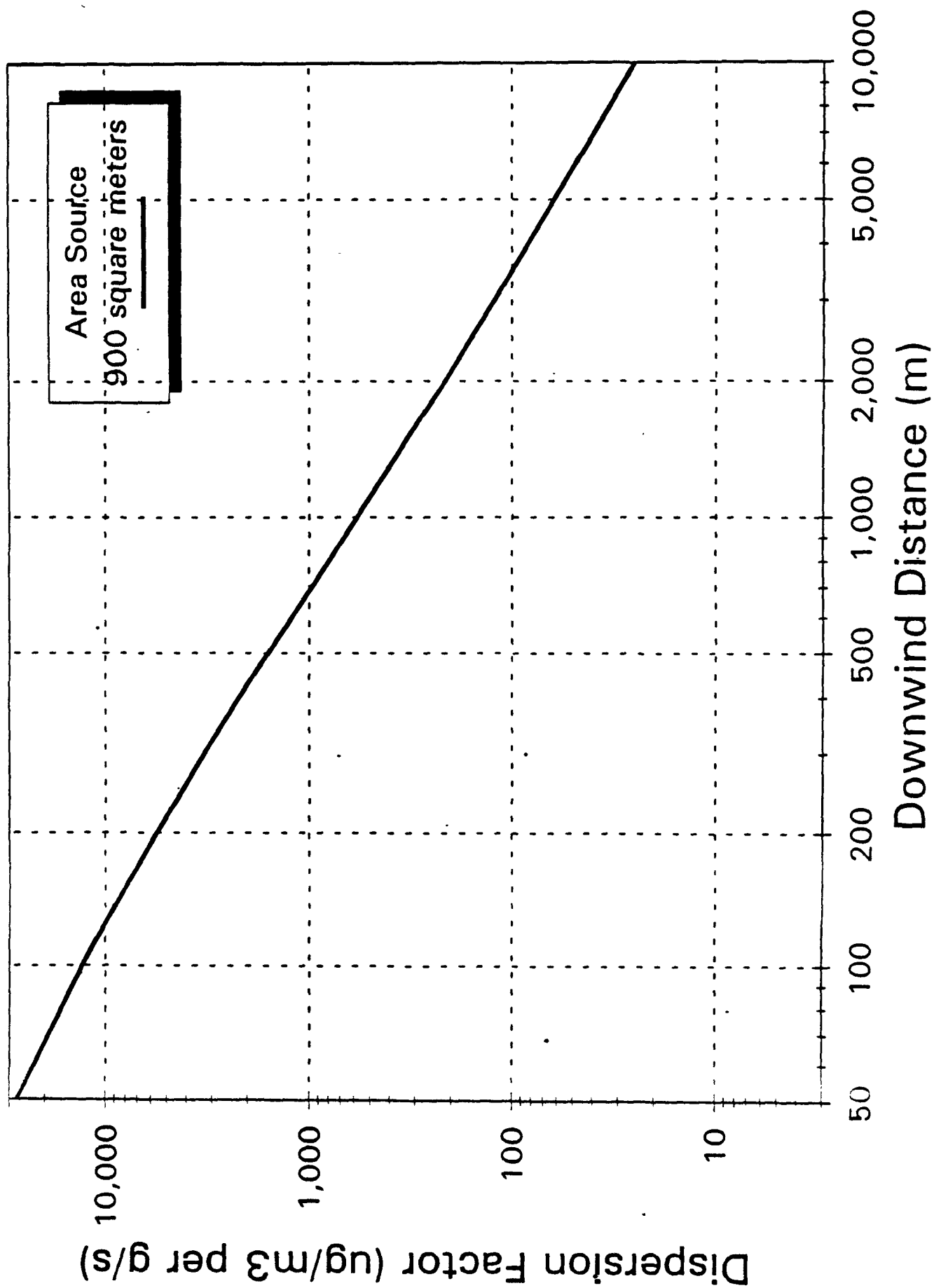


Figure 4. One-Hour Average Downwind Dispersion Factor Versus Distance for Bioventing Systems with Area Source Emissions

$$C_m = (ER)(F) \quad (\text{Eq. 5})$$

$$C_a = (ER)(F)(0.08) \quad (\text{Eq. 6})$$

where C_m = Maximum hourly ambient air concentration ($\mu\text{g}/\text{m}^3$);
 C_a = Annual average ambient air concentration ($\mu\text{g}/\text{m}^3$);
 ER = Emission rate (g/sec); and
 F = Dispersion factor from Figures 3 or 4 ($\mu\text{g}/\text{m}^3$ / g/sec).

Since TSCREEN provides maximum short-term estimates, the factor of 0.08 in Equation 6 is used to convert the short-term estimate to an annual average estimate. The 0.08 factor in Equation 6 was developed by the U.S. EPA for point sources. This factor has recently been revised and it is still under review by EPA and may be subject to further change. There is no EPA policy for converting from hourly to annual estimates for area sources. Various factors have been published that range up to 0.08¹². Factors up to 0.20 have been suggested for certain specific locations.¹³ Graphical estimation tools in lieu of these factors also have been proposed.^{14,15} It is assumed that this point source factor can be applied to area sources without greatly increasing the overall uncertainty of the air impact estimate. As previously stated, the recommended approach is to use ISCLT to estimate long-term concentrations.

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 $\mu\text{g}/\text{m}^3$ of concentration in the ambient air. They are available on EPA's Integrated Risk Information System (IRIS), the U.S. EPA's preferred source of toxicity information. User Support can be contacted at (513) 569-7254. The next best source of inhalation unit risk factors is EPA's Health Effects Assessment Summary Tables (HEAST) which are updated annually.¹⁶ Inhalation unit risk factors listed in IRIS as of January 1993 or in HEAST (FY 1992) are given in Table 4 for 168 volatile and semi-volatile organic compounds. This is an updated version of the same table contained in References 2 and 3. Similar information is given in Table 5 for selected semi-volatile organic compounds.

Table 4.

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

No.	Chemical	CAS Number	Carcinogenicity ^a Inhalation Unit Risk 1/(μg/m ³)	Chronic Toxicity ^a Inhalation RfC (mg/m ³)	Long-Term Action Levels				Short-Term Action Levels ^d Lowest OEL/100 (μg/m ³)
					Risk-Specific Concentrations for Carcinogenicity 10 ⁻⁶ 70-year Risk (μg/m ³)	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m ³)	Concentrations Based on Occupational Exposure ^d		
							Lowest OEL/1000 (μg/m ³)		
1	Acetaldehyde	75-07-0	2.2e-06 ^c	9e-03 ^c	0.45	9	180	1,800	
2	Acetic Acid	64-19-7	--	--	--	--	25	250	
3	Acetic anhydride	108-24-7	--	--	--	--	20	200	
4	Acetone	67-64-1	-- ^{ee}	(4e-01) ^b	--	400	1,780	17,800	
5	Acetonitrile	75-05-8	-- ^e	5e-02 ^f	--	50	67	670	
6	Acrolein	107-02-8	-- ^{ee}	2e-05 ^c	--	0.02	0.23	2.30	
7	Acrylic acid	79-10-7	-- ^e	3e-04 ^c	--	0.3	5.90	59	
8	Acrylonitrile	107-13-1	6.8e-05 ^c	2e-03 ^c	0.015 ^c	2	4.30	43	
9	Allyl alcohol	107-18-6	-- ^e	(2e-02) ^b	--	20	4.80	48	
10	Allyl chloride	107-05-1	-- ^{ee}	1e-03 ^c	--	1	3.00	30	
11	Aniline	62-53-3	1.6e-6 ^b	1e-03 ^c	0.63	1	7.60	76	
12	Anthracene	120-12-7	-- ^{ee}	(1e+00) ^b	--	1,000	0.20	2.00	
13	Benzaldehyde	100-52-7	-- ^e	(4e-01) ^b	--	400	--	--	
14	Benzene	71-43-2	8.3e-06 ^c	-- ^e	0.12	--	32	320	
15	Benzoic acid	65-85-0	-- ^{ee}	(1.4e+01) ^b	--	14,000	--	--	
16	Benzyl alcohol	100-51-6	-- ^e	(1e+00) ^b	--	1,000	--	--	
17	Benzyl chloride	100-44-7	5e-05 ^b	-- ^e	0.02	--	5	50	
18	Bromoform	75-25-2	1.1e-06 ^c	(7e-02) ^b	0.91	70	5	50	
19	1,3-Butadiene	106-99-0	2.8e-04 ^c	-- ^e	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	-- ^{ee}	(4e-01) ^b	--	400	152	1,520	

Table 4. (Continued)

No.	Chemical	CAS Number	Carcinogenicity ^a Inhalation Unit Risk 1/(μg/m³)	Chronic Toxicity ^a Inhalation RfC (mg/m³)	Long-Term Action Levels				Short-Term Action Levels ^d Lowest OEL/100 (μg/m³)
					Risk-Specific Concentrations for Carcinogenicity 10 ⁻⁶ 70-year Risk (μg/m³)	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m³)	Concentrations Based on Occupational Exposure ^d Lowest OEL/1000 (μg/m³)		
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	-- ^e	1e-02 ^f	--	10	12	120	
26	Carbon Tetrachloride	56-23-5	1.5e-05 ^e	(2.5e-03) ^b	0.0067	2.5	12.6	126	
27	Carbonyl Sulfide	463-58-1	-- ^e	-- ^e	--	--	--	--	
28	Catechol	120-80-9	-- ^e	-- ^e	--	--	20	200	
29	Chlorine	7782-50-5	-- ^e	-- ^e	--	--	1.5	15	
30	Chlorobenzene	108-90-7	-- ^e	2e-02 ^f	--	20	46	460	
31	Chlorodifluoromethane	75-45-6	-- ^e	-- ^e	--	--	3,540	35,400	
32	Chloroform	67-66-3	2.3e-05 ^e	(4e-02) ^b	0.043	40	9.78	98	
33	Chloromethyl methyl ether	107-30-2	-- ^e	-- ^e	--	--	--	--	
34	Chloropentafluoroethane	76-15-3	--	--	--	--	6,320	63,200	
35	Chloroprene	126-94-8	-- ^e	7e-03 ^f	--	7	35	350	
36	m-Cresol	108-39-4	-- ^e	(2e-01) ^b	--	200	22	220	
37	o-Cresol	95-48-7	-- ^e	(2e-01) ^b	--	200	22	220	
38	p-Cresol	106-44-5	-- ^e	(2e-01) ^b	--	200	22	220	
39	Cyanogen	460-19-5	-- ^e	(1.4e-01) ^b	--	140	20	200	
40	Cyclohexane	110-82-7	--	--	--	--	1,030	10,300	
41	Cyclohexanol	108-93-0	--	--	--	--	200	2,000	
42	Cyclohexanone	108-94-1	-- ^e	(18) ^b	--	18,000	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	-- ^e	-- ^e	--	--	0.34	3.4	

Table 4. (Continued)

No.	Chemical	CAS Number	Carcinogenicity ^a	Chronic Toxicity ^a	Long-Term Action Levels				Short-Term Action Levels ^d
					Inhalation Unit Risk 1/(μg/m ³)	Risk-Specific Concentrations for Carcinogenicity	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m ³)	Concentrations Based on Occupational Exposure ^d	
46	Dibutyl-O-Phthalate	84-74-2	-- ^{ee}	(4e-01) ^b	--		400	5.00	50
47	o-Dichlorobenzene	95-50-1	-- ^{ee}	2e-01 ^f	--		200	150	1,500
48	p-Dichlorobenzene	106-46-7	6.6e-6 ^b	8e-01 ^f	0.15		800	450	4,500
49	Dichloroethylether	111-44-4	3.3e-04 ^c	--	3.0e-03		--	29	290
50	Dichlorodifluoromethane	75-71-8	-- ^e	(0.7) ^b	--		200	4,950	49,500
51	1,1-Dichloroethane	75-34-3	-- ^{ee}	5e-01 ^f	--		500	400	4,000
52	1,2-Dichloroethane	107-06-2	2.6e-05 ^c	--	0.038 ^c		--	4.00	40
53	1,1-Dichloroethylene	75-35-4	5e-05 ^c	(3e-02) ^b	0.020		30	4.00	40
54	cis-1,2-dichloroethylene	156-59-2	-- ^{ee}	(4e-02) ^b	--		40	790	7,900
55	trans-1,2-dichloroethylene	156-60-5	-- ^e	(7e-02) ^b	--		70	790	7,900
56	Dichloromethane	75-09-2	4.7e-07 ^c	3e+00 ^f	2.1		3,000	174	1,740
57	Dichloromono fluoromethane	75-43-4	--	--	--		--	40	400
58	1,2-Dichloropropane	78-87-5	2e-05 ^b	4e-3 ^c	0.050		4	347	3,470
59	1,3-Dichloropropene	542-75-6	3.7e-05 ^f	2e-02 ^c	0.027		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	-- ^e	(7e-03) ^b	--		7	25	250
64	Diethyl ether	60-29-7	--	(7e-01) ^b	--		700	1,200	12,000
65	Dimethylamine	124-40-3	-- ^e	-- ^c	--		--	9.2	92
66	Dimethyl formamide	68-12-2	-- ^e	3e-02 ^c	--		30	30	300
67	1,1-Dimethyl hydrazine	57-14-7	1e-03 ^f	-- ^c	1e-03		--	1	10
68	2,4-Dinitrophenol	51-28-5	-- ^e	(7e-03) ^b	--		7		--

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 (μg/m ³)	Concentrations Based on Occupational Exposure ^d		
							10 ⁻⁶ 70-year Risk (μg/m ³)	Lowest OEL/1000 (μg/m ³)	
69	1,4-Dioxane	123-91-1	3.1e-03 ^b	-- ^c	3.2e-04	--	90	900	
70	Diphenyl	92-52-4	-- ^c	(1.8e-01) ^b	--	180	1.00	10	
71	Epichlorohydrin	106-89-8	1.2e-06 ^c	1e-3 ^c	0.83	1.0	7.6	76	
72	1,2-Epoxybutane	106-88-7	-- ^c	2e-02 ^c	--	20	--	--	
73	Ethanol	64-17-5	--	--	--	--	1,880	18,800	
74	Ethyl acetate	141-78-6	-- ^c	(3.2e+00) ^b	--	3,200	1,400	14,000	
75	Ethyl acrylate	140-88-5	1.4e-05 ^b	-- ^c	0.071	--	20	200	
76	Ethyl amine	75-04-7	--	--	--	--	18	180	
77	Ethylbenzene	100-41-4	-- ^c	1e-00 ^c	--	1,000	434	4,340	
78	Ethyl bromide	74-96-4	-- ^c	-- ^c	--	--	22	220	
79	Ethyl carbamate	51-79-6	-- ^c	-- ^c	--	--	--	--	
80	Ethyl chloride	75-00-3	-- ^c	1e+01 ^c	--	10,000	2,600	26,000	
81	Ethylenediamine	107-15-3	-- ^c	0.07	--	70	25	250	
82	Ethylene dibromide	106-93-4	2.2e-04 ^c	-- ^c	4.5e-03	--	--	--	
83	Ethylene glycol	107-21-1	-- ^c	(7.0e+00) ^b	--	7,000	127	1,270	
84	Ethylene imine	151-56-4	-- ^c	--	--	--	0.88	8.80	
85	Ethylene oxide	75-21-8	1.0e-04 ^c	(3.6e+00) ^b	0.010	3,600	1.80	18	
86	Formaldehyde	50-00-0	1.3e-05 ^c	(7e-01) ^b	0.077	700	1.2	12	
87	Formic Acid	64-18-6	-- ^c	(7e+00) ^b	--	7,000	9.00	90	
88	Furan	110-00-9	-- ^c	(4.0e-03) ^b	--	4	--	--	
89	Glycerol	56-81-5	--	--	--	--	5.00	50	
90	n-Heptane	142-82-5	-- ^c	-- ^c	--	--	1,600	16,000	
91	n-Hexane	110-54-3	-- ^c	2e-01 ^c	--	200	176	1,760	

Table 4. (Continued)

	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 (μg/m ³)	Concentrations Based on Occupational Exposure ^d	Lowest OEL/1000 (μg/m ³)	
No.			Inhalation Risk 1/(μg/m ³)	Inhalation RfC (mg/m ³)					
92	Hydrazine	302-01-2	4.9e-03 ^c	-- ^e	2.0e-04	--	0.1		1
93	Hydrochloric acid	7647-01-0	-- ^e	7e-03 ^c	--	7	7.5		75
94	Hydrogen cyanide	74-90-8	-- ^e	(0.07) ^b	--	70	11		110
95	Hydrogen Sulfide	7783-06-4	-- ^e	9e-04 ^c	--	0.9	14		140
96	Isobutanol	78-83-1	--	(1.1e+00) ^b	--	1,100	150		1,500
97	Isobutyl acetate	110-19-0	--	--	--	--	700		7,000
98	Isopropyl alcohol	67-63-0	-- ^e	-- ^e	--	--	983		9,830
99	Isopropyl amine	75-31-0	--	--	--	--	12		120
100	Isopropylbenzene	98-82-8	-- ^e	(1.4e-01) ^b	--	140	245		2,450
101	Methanol	67-56-1	-- ^e	(2e+00) ^b	--	2,000	260		2,600
102	Methyl acetate	79-20-9	-- ^e	(4e+00) ^b	--	4,000	606		6,060
103	Methyl acrylate	96-33-3	-- ^e	(1.1e-01) ^b	--	110	35		350
104	Methyl amine	74-89-5	--	--	--	--	6.4		64
105	Methyl bromide	74-83-9	-- ^e	5e-3 ^c	--	5	19		190
106	Methyl-tert-butyl-ether	1634-04-4	-- ^e	5e-01 ^c	--	500	--		--
107	Methyl chloride	74-87-3	1.8e-06 ^c	-- ^e	0.55	--	103		1,030
108	Methylcyclohexane	108-87-2	--	3e+00 ^c	--	3,000	1,600		16,000
109	Methyl-ethyl-ketone	78-93-3	-- ^e	1e-00 ^c	--	1,000	590		5,900
110	Methyl formate	107-31-3	--	--	--	--	246		2,460
111	Methyl hydrazine	60-34-4	3e-04 ^b	-- ^e	3.3e-03	--	0.38		3.8
112	Methyl iodide	74-88-4	-- ^e	-- ^e	--	--	10		100
113	Methyl-Isobutyl-Ketone	108-10-1	-- ^e	8e-02 ^f	--	80	205		2,050
114	Methyl isocyanate	624-83-9	-- ^e	-- ^e	--	--	0.047		0.47

Table 4. (Continued)

No.	Chemical	CAS Number	Carcinogenicity ^a Inhalation Unit Risk 1/(μg/m ³)	Chronic Toxicity ^a Inhalation RfC (mg/m ³)	Long-Term Action Levels			Short-Term Action Levels ^d Lowest OEL/100 (μg/m ³)
					Risk-Specific Concentrations for Carcinogenicity 10 ⁻⁶ 70-year Risk (μg/m ³)	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m ³)	Concentrations Based on Occupational Exposure ^d Lowest OEL/1000 (μg/m ³)	
115	Methyl-Isopropyl-Ketone	563-80-4	--	--	--	--	705	7,050
116	Methyl mercaptan	74-93-1	-- ^e	-- ^e	--	--	0.98	98
117	Methyl methacrylate	80-62-6	-- ^e	(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	-- ^e	(2.5e-01) ^b	--	250	240	2,400
120	Monoethanolamine	141-43-5	--	--	--	--	7.50	75
121	Morpholine	110-91-8	--	--	--	--	70	700
122	Naphthalene	91-20-3	-- ^e	--	--	--	50	500
123	2-Nitropropane	79-46-9	2.7e-03 ^c	2e-02 ^c	3.7e-04	20	35	350
124	N-Nitrosodimethylamine	62-75-9	1.4e-02 ^c	-- ^e	7.1e-05	--	--	--
125	N-Nitrosomorpholine	59-89-2	--	--	--	--	--	--
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	-- ^e	-- ^e	--	--	0.20	2
130	Phenol	108-95-2	-- ^e	(2.1e+00) ^b	--	2,000	19	190
131	Phosgene	75-44-5	-- ^e	-- ^e	--	--	0.4	4
132	Phosphine	7803-51-2	-- ^e	3e-05 ^f	--	0.03	0.4	4
133	Phthalic anhydride	85-44-9	-- ^e	1.2e-01 ^f	--	120	6.00	60
134	Propane	74-98-6	--	--	--	--	1,800	18,000
135	1,2-Propanediol	57-55-6	-- ^e	-- ^e	--	--	--	--
136	1-Propanol	71-23-8	-- ^e	-- ^e	--	--	492	4,920
137	beta-Propiolactone	57-57-8	-- ^e	-- ^e	--	--	1.5	15

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 (μg/m ³)	Concentrations Based on Occupational Exposure ^d		
							10 ⁻⁶ 70-year Risk (μg/m ³)	Lowest OEL/1000 (μg/m ³)	
138	Propionaldehyde	123-38-7	--	--	--	--	--	--	--
139	Propionic acid	79-09-4	-- ^e	-- ^e	--	--	30	30	300
140	n-Propyl-Acetate	109-60-4	--	--	--	--	835	835	8,350
141	Propylene oxide	75-56-9	3.7e-06 ^e	3e-02 ^e	0.27	30	48	48	480
142	1,2-Propylenimine	75-55-8	-- ^e	-- ^e	--	--	4.7	4.7	47
143	Pyridine	110-86-1	-- ^e	(4e-03) ^b	--	4	15	15	150
144	Quinone	106-51-4	-- ^e	-- ^e	--	--	0.4	0.4	4
145	Styrene	100-42-5	-- ^e	1.0e+00 ^f	--	1000	213	213	2,130
146	1,1,1,2-Tetrachloro-2,2-Difluoroethane	76-11-9	--	--	--	--	4,170	4,170	41,700
147	1,1,2,2-Tetrachloroethane	79-34-5	5.8e-05 ^{e,e}	-- ^e	0.017	--	6.90	6.90	69
148	Tetrachloroethylene	127-18-4	5.8e-07 ^e	(3.5e-2) ^b	1.7	35	170	170	1,700
149	Tetrahydrofuran	109-99-9	-- ^e	-- ^e	--	--	590	590	5,900
150	Toluene	108-88-3	-- ^{e,e}	4e-01 ^e	--	400	375	375	3,750
151	p-Toluidine	106-49-0	5.4e-05 ^b	-- ^e	0.019	--	8.80	8.80	88
152	1,1,1-Trichloroethane	71-55-6	-- ^{e,e}	1.0e+00 ^f	--	1,000	1,900	1,900	19,000
153	1,1,2-Trichloroethane	79-00-5	1.6e-05 ^{e,e}	1.4e-02 ^e	0.063	14	45	45	450
154	Trichloroethylene	79-01-6	-- ^e	-- ^e	--	--	269	269	2,690
155	Trichlorofluoromethane	75-69-4	-- ^e	7.0e-01 ^f	--	700	5,620	5,620	56,200
156	1,2,3-Trichloropropane	96-18-4	-- ^e	2.0e-02 ^e	--	20	60	60	600
157	1,1,2-Trichloro-1,2,2-Trifluoroethane	76-13-1	-- ^e	(2.7e+01) ^b	--	27,000	7,600	7,600	76,000
158	Triethylamine	121-44-8	-- ^e	7e-3 ^e	--	7	40	40	400
159	Trifluorobromomethane	75-63-8	--	--	--	--	6,090	6,090	60,900
160	1,2,3-Trimethylbenzene	526-73-8	--	--	--	--	123	123	1,230

Table 4. (Continued)

No.	Chemical	CAS Number	Carcinogenicity ^a	Chronic Toxicity ^a	Long-Term Action Levels				Short-Term Action Levels ^d
					Inhalation Unit Risk 1/(μg/m ³)	Risk-Specific Concentrations for Carcinogenicity	RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m ³)	Concentrations Based on Occupational Exposure ^d	
								10 ⁻⁶ 70-year Risk (μg/m ³)	
161	1,2,4-Trimethylbenzene	95-63-6	--	--	--	--	123	Lowest OEL/1000 (μg/m ³)	Lowest OEL/100 (μg/m ³)
162	1,3,5-Trimethylbenzene	108-67-8	--	--	--	--	123		1,230
163	Vinyl acetate	108-05-4	-- ^e	2e-01 ^e	--	200	30		300
164	Vinyl bromide	593-60-2	3.2e-05 ^f	--	0.031	--	20		200
165	Vinyl-chloride	75-01-4	8.4e-05 ^e	--	0.012	--	2.60		26
166	m-Xylene	108-38-3	-- ^e	(7) ^b	--	7000	434		4,340
167	o-Xylene	95-47-6	-- ^e	(7) ^b	--	7000	434		4,340
168	p-Xylene	106-42-3	-- ^e	-- ^c	--	--	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 (1/93) 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.

^f Available in the Health Effects Assessment Summary Tables (HEAST, FY1992).

Table 5.

Long-Term and Short-Term Health-Based Action Levels for Selected Semi-Volatile Organic Compounds in Air

No.	Chemical	CAS Number	Carcinogenicity ^a Inhalation Risk 1/(μg/m³)	Chronic Toxicity ^a Inhalation RfC (mg/m³)	Long-Term Action Levels				Short-Term Action Levels ^d Lowest OEL/100 (μg/m³)
					Risk-Specific Concentrations for Carcinogenicity		RfC-Based Concentrations for Non-Carcinogenic Effects (μg/m³)	Concentrations Based on Occupational Exposure ^d Lowest OEL/1000 (μg/m³)	
					10 ⁻⁶ 70-year Risk (μg/m³)				
1	Acenaphthene	83-32-9	-- ^e	(2.1e-01) ^b	--		210	--	--
2	2-Acetoaminofluorene	53-96-3	--	--	--		--	--	--
3	2-Acetylfuran	1192-62-7	--	--	--		--	--	--
4	Benzidine	92-87-5	6.7e-02 ^c	(1.1e-02) ^b	1.5e-05	10.5	--	--	--
5	Benz(a)anthracene	56-55-3	-- ^e	-- ^e	--		--	--	--
6	Benzo(a)pyrene	50-32-8	1.7e-03 ^b	--	5.9e-04	--	0.2 ^f	--	2.0
7	Benzo(a)fluoranthene	205-99-2	-- ^e	-- ^e	--		--	--	--
8	Benzo(g,h,i)perylene	191-24-2	-- ^e	-- ^e	--		--	--	--
9	Benzo(k)fluoranthene	207-08-9	-- ^e	-- ^e	--		--	--	--
10	Bis(2-ethylhexyl)phthalate	117-81-7	4e-06 ^b	(7e-02) ^b	0.25	70	5	50	50
11	Chlordane	57-74-9	3.7e-04 ^c	(2.1e-04) ^b	2.7e-03	0.21	0.5	5	5
12	Chrysene	218-01-9	--	--	--		0.2 ^f	2.0 ^e	2.0 ^e
13	Cresol	1319-77-3	-- ^{e,e}	(2e-01) ^b	--	200	22	220	220
14	Dioxin (2,3,7,8-TCDD)	1746-01-6	--	--	--		--	--	--
15	Dibenzofuran	132-64-9	-- ^{e,e}	-- ^e	--		--	--	--
16	Dibenzo(a,h)anthracene	53-70-3	-- ^e	-- ^e	--		--	--	--
17	Di-n-butylphthalate	84-74-2	-- ^{e,e}	(3.5e-01) ^b	--	350	5	50	50
18	Ethylenamine	593-67-9	--	--	--		--	--	--
19	Fluoranthene	206-44-0	-- ^{e,e}	(1.4e-01) ^b	--	140	--	--	--
20	Fluorene	86-73-7	-- ^{e,e}	(1.4e-01) ^b	--	140	--	--	--
21	Heptachlor	76-44-8	1.3e-03 ^c	(1.8e-03) ^b	7.7e-04	1.8	0.5	5	5

Table 5. (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 (µg/m³)	Concentrations Based on Occupational Exposure ^d		
								10 ⁻⁶ 70-year Risk (µg/m³)	
22	Hexachlorocyclopentadiene	77-47-4	-- ^{e,e}	Inhalation RfC (mg/m³) 7e-5 ^f	--	0.07	0.1	1.0	
23	Indeno(1,2,3,CD)pyrene	193-39-5	--	--	--	--	--	--	
24	Lindane	58-89-9							
25	Maleic Anhydride	108-31-6	-- ^e	(3.5e-01) ^b	--	350	1	10	
26	2-Methylnaphthalene	91-57-6	--	--	--	--	--	--	
27	p-Nitrosodiphenylamine	156-10-5	--	--	--	--	--	--	
28	Nitrobenzene	98-95-3	-- ^e	2e-3	--	2.0	5	50	
29	PCBs	1336-36-3	2.2e-03 ^b	-- ^e	4.5e-04	--	--	--	
30	PAHs	--	--	--	--	--	0.2 ^e	2.0 ^e	
31	Parathion	56-38-2	-- ^e	(2.1e-02) ^b	--	21	0.1	1.0	
32	Pyrene	129-00-0	-- ^{e,e}	(1.1e-01) ^b	--	105	--	--	
33	Tridecane	629-50-5	--	--	--	--	--	--	
34	Undecane	1120-21-4	--	--	--	--	--	--	

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.

^f Available in the Health Effects Assessment Summary Tables (HEAST, FY 1992).

^g As coal tar pitch volatiles.

Equation 7 can be used to estimate the cancer risk at a specified distance downwind of the bioventing system. Cancer risk is a measure of the increased probability of developing cancer in a lifetime as a result of the exposure in question. Equation 7 assumes continuous exposure (24 hours/day, 365 days/year for 70 years) to the estimated annual average concentration in air.

$$R = (C_a)(IUR) \quad (\text{Eq. 7})$$

where R = Cancer risk from long-term exposure to a specific compound in air (dimensionless);

C_a = Annual average ambient concentration, from Equation 6 ($\mu\text{g}/\text{m}^3$); and

IUR = Inhalation unit risk factor, from Table 4 or 5 ($\mu\text{g}/\text{m}^3$)⁻¹.

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 7. If more than one contaminant is present, the cancer risks for each contaminant can be summed to derive the total cancer risk at a specified distance downwind of the source.

Non-Cancer Effects Due to Long-Term Exposure

Non-cancer effects can be evaluated by using chronic inhalation reference concentrations (RfCs). An inhalation RfC is an estimate (with uncertainty spanning perhaps an order of magnitude) of continuous exposure of the human population to contaminants in the air that is likely to be without appreciable risk of deleterious effects during a lifetime. During the past three years, the EPA has become increasingly active in the development of chemical specific RfCs.

If inhalation RfCs were not available from either IRIS or HEAST, then chronic oral reference dose (RfD) data (in $\text{mg}/\text{kg}/\text{day}$) 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 $\mu\text{g}/\text{mg}$ to derive a value in $\mu\text{g}/\text{m}^3$. This methodology was selected as the best available approach for this screening document. The EPA, however, does not condone derivation of RfCs from data for other routes of exposure on a chemical specific basis.

The EPA considers the minimum basis for the derivation of an RfC to be a properly conducted inhalation study that examines portal of entry effects. Portal of entry effects are particularly important with respect to inhalation. There are many known cases where respiratory effects due to inhalation exposure are much more severe than effects resulting from equivalent oral doses. Therefore, ambient air action levels based on extrapolated oral data should be used cautiously, since there may be significant differences between the oral and inhalation exposure pathways.

For compounds lacking RfC or RfD values, action levels were based on occupational exposure levels recommended by the Occupational Safety and Health Administration (OSHA)¹⁷ and the American Conference of Governmental Industrial Hygienists (ACGIH).¹⁸ 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. It should be noted that occupational exposure levels are not intended for evaluation or control of community air pollution or in estimating the toxic potential of continuous, uninterrupted exposures. Therefore, ambient air action levels based on occupational exposure limits are not precise distinctions between safe and dangerous ambient air concentrations, nor are they necessarily indices of toxicity.

Long-term ambient air action level concentrations for non-carcinogens based on RfCs, extrapolated RfDs and occupational exposure levels are also listed in Tables 4 and 5. The action levels are in units of $\mu\text{g}/\text{m}^3$ to facilitate comparison to the ambient air concentrations estimated from Equation 6.

Short-Term Exposure

The short-term (one hour) action levels, in $\mu\text{g}/\text{m}^3$, are presented in the last column of Tables 4 and 5. 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 Tables 4 and 5 (or to derive values for compounds not listed in the tables), 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 Tables 4 and 5 can be compared directly with the estimated maximum hourly ambient air concentrations obtained by using Equation 5 and Figures 3 and 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 a bioventing system and compare these values to the action level concentrations listed in Tables 4 and 5.

Step 1 First, collect all necessary information. For this example, assume a site that has approximately 10,000 m³ of soil contaminated with benzene and benzo(a)pyrene at concentrations in the soil at 100 µg/g and 10.0 µg/g, respectively. A bioventing system will be used to treat the silty soil. The bulk density of the soil at the site averages about 1.5 g/cm³. The exhaust gas flowrate is unknown. The stack diameter is assumed to be around 0.1 m. For this initial screening evaluation, it is assumed that no air pollution controls are used.

Pilot-scale testing showed soil gas concentrations of benzene and benzo(a)pyrene at 100,000 µg/m³ and 10 µg/m³, respectively. The only source of emission is assumed to be the stack (point source). The bioventing 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 maximum average emission rate for the six-month operation period. Using Equation 1, the average long-term emission rate of benzene would be:

$$ER_{avg} = \frac{(10,000)(100)(1.5)(1)}{(1.58 \times 10^7)} = 9.49 \times 10^{-2} \text{ g/sec}$$

The average long-term emission rate for benzo(a)pyrene is 9.49×10^{-3} g/sec. These rates assume that 100% of the contaminant is lost to the atmosphere. This is obviously an overly conservative assumption for the VOCs if control devices are used or if the VOCs are biodegraded and for semi-volatile organic compounds.

- Step 3** Estimate the exhaust gas flow rate for the bioventing system. The air-filled porosity is assumed to be 0.31 from Table 1 for silty soils. The gas flow rate can be estimated using Equation 3:

$$Q = \left(\frac{1.0}{1440} \right) (10,000) (0.31) = 2.2 \text{ m}^3/\text{min}$$

- Step 4** Estimate the VOC emission rate of each compound from the bioventing system. The appropriate data are inserted into Equation 2. For benzene, the emission rate would be:

$$(100,000) \left(\frac{2.2}{60} \right) (10^{-6}) = 3.67 \times 10^{-3} \text{ g/sec}$$

The VOC emission rate for benzo(a)pyrene is 3.67×10^{-7} g/sec.

- Step 5** Compare the estimated emission rates from Step 4 to those from Step 2. The comparison is:

Compound	Equation 1 Emission Rate (g/sec)	Equation 2 Emission Rate (g/sec)
Benzene	9.49×10^{-2}	3.67×10^{-3}
Benzo(a)pyrene	9.49×10^{-3}	3.67×10^{-7}

The benzene emission rate estimated using Equation 2 is nearly the same as the benzene emission rate (in g/sec) estimated using Equation 1 based on the total mass of benzene present at the site. This is expected since most of the VOCs may be volatilized to the atmosphere. The estimated emission rate from Equation 2 for benzo(a)pyrene is much lower than the maximum long-term emission rate because benzo(a)pyrene is not very volatile at ambient temperatures.

Step 6

Estimate the downwind ambient air concentrations. From Figure 3, the maximum hourly ambient air concentration at a distance of 400 meters for a bioventing system is approximately $1420 \mu\text{g}/\text{m}^3$ per g/sec emission rate. This corresponds to an annual average dispersion factor of $114 \mu\text{g}/\text{m}^3$ per g/s ($1420 \times 0.08 = 114$). Using Equation 5, the hourly average ambient air concentration for benzene would be:

$$C_m = (3.67 \times 10^{-3})(1420) = 5.2 \mu\text{g}/\text{m}^3$$

Using Equation 6, the annual average air ambient concentration for benzene would be:

$$C_a = (5.2)(0.08) = 0.42 \mu\text{g}/\text{m}^3$$

The ambient air concentrations estimated from Equations 5 and 6 are presented in Table 6.

Step 7

Compare the downwind concentrations to the action level ambient air concentrations. The short-term and long-term action levels from Tables 4 and 5 for the compounds of interest are presented in Table 7. Of the estimated maximum hourly ambient concentrations, the benzene concentration is above the action level. The action level is based on a 70-year risk. Since, this system will be operated for much less than 70 years, the action level (AL) can be adjusted by the following:

$$AL_{\text{adjusted}} = (AL) \left(\frac{70}{\text{Length of operation in years}} \right) = (0.12) \left(\frac{70}{0.5} \right) = 16.8 \mu\text{g}/\text{m}^3$$

The benzene concentration is not above the adjusted action level.

Step 8

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 not necessary.

Table 6.

Estimated Emission Rates and Ambient Air Concentrations

	Soil Concentration For Example Problem ($\mu\text{g/g}$)	Emission Rate (g/s)	Ambient Concentrations ($\mu\text{g/m}^3$)	
			Maximum 1 Hourly	Annual Average
Benzene	100	3.67×10^{-3}	5.2	0.42
Benzo(a)pyrene	10.0	3.67×10^{-7}	5.2×10^{-4}	4.2×10^{-5}

Table 7.

Action Level Concentrations

	Action Levels $\mu\text{g/m}^3$	
	Short-Term	Long-Term
Benzene	320	0.12^1
Benzo(a)pyrene	2.0	$5.9 \times 10^{-4}^1$

¹Based on 10^{-6} , 70-year risk.

The air impacts should be re-examined, however, when the site-specific data become available, if the inputs differ from the default values. Also, it would be advisable to perform an ambient air monitoring program during remediation to document the actual worker and community exposures.

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. For example, emission models assume typical operating conditions, dispersion models assume Gaussian distribution of the plume, 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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APPENDIX A

**PHYSICAL PROPERTY DATA
FOR SELECTED ORGANIC COMPOUNDS**
(For compounds in Table 4 of the report)

Source: Eklund, B. and C. Albert. Models for Estimating Air Emission Rates from Superfund Remedial Actions. EPA-451/R-93-001. March 1993.

Appendix A - Physical Property Data

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)*	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (μg/m ³)*	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
1	Acetaldehyde	75-07-0	C ₂ H ₄ O	44.00	760	0.1240	1.80E+09	9.50e-05	-4.02	inf	1.41e-05	-
2	Acetic acid	64-19-7	C ₂ H ₄ O ₂	60.06	15.41	0.1300	4.97E+07	6.27e-02	-1.20	inf	1.20e-05	-
3	Acetic anhydride	108-24-7	C ₄ H ₆ O ₃	102.09	5.266	0.2350	2.89E+07	5.91e-06	-5.23	--	9.33e-06	-
4	Acetone	67-64-1	C ₃ H ₆ O	58.08	266	0.1240	8.30E+08	2.50e-05	-4.60	inf	1.14e-5	-0.24
5	Acetonitrile	75-05-8	C ₂ H ₃ N	41.06	90	0.1280	1.99E+08	5.80e-06	-5.24	inf	1.66e-5	-0.34
6	Acrolein	107-02-8	C ₃ H ₄ O	56.1	244.2	0.1050	7.36E+08	5.66e-05	-4.25	208,000	1.22e-5	-
7	Acrylic acid	79-10-7	C ₃ H ₄ O ₂	72.1	5.2	0.0908	2.02E+07	1.00e-07	-7.00	inf	1.08e-5	0.13
8	Acrylonitrile	107-13-1	C ₃ H ₃ N	53.06	114	0.1220	3.25E+08	8.80e-05	-4.06	73,500	1.34e-5	-0.92
9	Allyl alcohol	107-18-6	C ₃ H ₆ O	58.08	23.3	0.1140	7.27E+07	1.80e-05	-4.74	inf	1.14e-5	-0.22
10	Allyl chloride	107-05-1	C ₃ H ₅ Cl	76.53	368	0.0	1.51E+09	3.71e-01	-0.43	3,600	0.0	--
11	Aniline	62-53-3	C ₆ H ₇ N	93.13	1	0.0700	5.01E+06	2.60e-06	-5.59	35,000	8.3e-6	-
12	Anthracene	120-12-7	C ₁₄ H ₁₀	178.23	1.3E-06	0.0	1.25E+01	6.75e-02	-1.17	1.3	0.0	4.45
13	Benzaldehyde	100-52-7	C ₇ H ₆ O	106.12	1	--	5.70E+06	4.23e-05	-4.37	3,000	--	--
14	Benzene	71-43-2	C ₆ H ₆	78.12	95.2	0.0932	4.00E+08	5.50e-03	-2.26	1,780	9.8e-6	2.12
15	Benzoic acid	65-85-0	C ₇ H ₆ O ₂	122.12	0.00704	0.0	4.62E+04	1.82e-08	-7.74	2,900	7.97e-6	--
16	Benzyl alcohol	100-51-6	C ₇ H ₈ O	108.14	0.15	--	8.72E+05	6.10e-07	-6.21	35,000	--	--
17	Benzyl chloride	100-44-7	C ₆ H ₅ CH ₂ Cl	126.6	1.21	0.0750	8.23E+06	4.33e-04	-3.36	1,619	7.8e-6	2.63
18	Bromoform	75-25-2	CHBr ₃	252.77	5.6	0.0	7.61E+07	5.94e-04	-3.23	3,190	0.0	--
19	1,3-Butadiene	106-99-0	C ₄ H ₆	54.09	2100	0.2490	6.09E+09	1.42e-01	-0.85	735	1.8e-5	1.99
20	N-Butane	106-97-8	C ₄ H ₁₀	58.12	1820	0.2490	5.69E+09	2.91e-01	-0.54	61	--	--
21	2-Butanol	15892-23-6	C ₄ H ₁₀ O	74.12	10	--	3.98E+07	2.20e-06	-5.66	184,000	--	--
22	N-Butanol	71-36-3	C ₄ H ₁₀ O	74.12	6.5	0.0800	2.59E+07	2.20e-06	-5.66	77,000	9.3e-6	--
23	N-Butyl-Acetate	123-86-4	C ₈ H ₁₆ O ₂	116.16	15	0.0	9.37E+07	1.64e-04	-3.79	14,000	0.0	--
24	Tert-Butyl-Alcohol	75-65-0	C ₄ H ₁₀ O	74.12	0.17	--	6.77E+05	2.20e-06	-5.66	inf	--	--
25	Carbon disulfide	75-15-0	CS ₂	76.13	366	0.1040	1.50E+09	1.68e-02	-1.77	2,900	1.0e-5	2.00

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)*	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (µg/m ³)*	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
26	Carbon tetrachloride	56-23-5	CCl ₄	153.82	113	0.0632	9.34E+08	3.00e-02	-1.52	800	8.8e-6	2.83
27	Carbonyl sulfide	463-58-1	COS	60.1	—	—	—	—	—	—	—	—
28	Catechol	120-80-9	C ₆ H ₄ (OH) ₂	110.1	—	—	—	—	—	—	—	—
29	Chlorine	7782-50-5	Cl ₂	70.9	—	—	—	—	—	—	—	—
30	Chlorobenzene	108-90-7	C ₆ H ₅ Cl	112.56	11.8	0.0730	7.14E+07	3.93e-03	-2.41	488	8.7e-6	2.84*
31	Chlorodifluoromethane	75-45-6	CHClF ₂	86.47	—	—	—	1.00e-01	-1.00	2	—	—
32	Chloroform	67-66-3	CHCl ₃	119.38	208	0.0888	1.33E+09	3.39e-03	-2.47	9,300	1.0e-5	1.97*
33	Chloromethyl methyl ether	107-30-2	C ₂ H ₅ Cl ₆	80.51	—	—	—	9.12x10 ⁻⁶	-5.04	2.5x10 ⁶	—	0.0
34	Chloropentafluoroethane	76-15-3	C ₂ ClF ₅	154.47	—	—	—	2.45e-01	-0.61	—	—	—
35	Chloroprene	126-99-8	C ₄ H ₃ Cl	88.5	273	0.1040	1.12E+09	3.35e-01	-0.475	—	1.0e-5	—
36	M-Cresol	108-39-4	C ₇ H ₈ O	108.14	0.08	0.0740	4.65E+05	4.43e-07	-6.35	25,000	1.0e-5	1.97
37	O-Cresol	95-48-7	C ₇ H ₈ O	108.14	0.24	0.0740	1.40E+06	2.60e-06	-5.59	31,000	8.3e-6	—
38	P-Cresol	106-44-5	C ₇ H ₈ O	108.14	0.11	0.0740	6.39E+05	4.43e-07	-6.35	24,000	1.0e-5	—
39	Cyanogen	460-19-5	C ₂ N ₂	52.04	3980	—	1.11E+10	4.96e-03	-2.30	9,300	—	—
40	Cyclohexane	110-82-7	C ₆ H ₁₂	84.16	100	0.0839	4.52E+08	1.37e-02	-1.86	100	9.1e-6	3.44
41	Cyclohexanol	108-93-0	C ₆ H ₁₂ O	100.16	1.22	0.2140	6.57E+06	4.47e-06	-5.35	38,200	8.31e-6	1.23
42	Cyclohexanone	108-94-1	C ₆ H ₁₀ O	98.14	4.8	0.0784	2.53E+07	4.13e-06	-5.38	23,000	8.62e-6	—
43	Cyclohexene	110-83-8	C ₆ H ₁₀	82.15	—	—	—	1.03e+01	1.01	213	—	2.86
44	Cyclopentane	287-92-3	C ₅ H ₁₀	70.13	317.44	—	1.20E+09	1.00e-02	-2.00	156	—	—
45	Diazomethane	334-88-3	CH ₂ N ₂	42.04	—	—	—	—	—	?	—	—
46	Dibutyl-O-Phthalate	84-74-2	C ₁₆ H ₂₂ O ₄	278.35	1.00E-05	0.0439	—	2.80e-07	-6.55	400	7.8e-6	5.60
47	O-Dichlorobenzene	95-50-1	C ₆ H ₄ Cl ₂	147.00	1	0.0690	7.90E+06	1.94e-03	-2.71	145	7.9e-6	3.60
48	P-Dichlorobenzene	106-46-7	C ₆ H ₄ Cl ₂	147.00	1.2	0.0690	9.48E+06	1.60e-03	-2.80	79	7.9e-6	3.38
49	Dichloroethylether	111-44-4	C ₄ H ₈ Cl ₂ O	143.02	1.4	—	1.08E+07	—	—	?	7.9e-6	3.39
50	Dichlorodifluoromethane	75-71-8	CCl ₂ F ₂	120.91	4870	0.0	3.16E+10	4.01e-01	-0.40	280	0.0	2.16

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)*	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (µg/m ³)*	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
51	1,1-Dichloroethane	75-34-3	C ₂ H ₄ Cl ₂	98.96	234	0.0919	1.24E+09	1.54E-02	-1.81	5,500	9.9E-6	1.79
52	1,2-Dichloroethane	107-06-2	C ₂ H ₄ Cl ₂	98.96	80	0.1040	4.26E+08	1.20E-03	-2.92	8,690	9.9E-6	1.48
53	1,1-Dichloroethylene	75-35-4	C ₂ H ₂ Cl ₂	96.94	600	0.1040	3.13E+09	2.59E-02	-1.59	210	--	1.84
54	cis-1,2-Dichloroethylene	156-59-2	C ₂ H ₂ Cl ₂	96.94	208		1.08E+09	4.55E-03	-2.34	800	--	0.70
55	trans-1,2-Dichloroethylene	156-60-5	C ₂ H ₂ Cl ₂	96.94	324		1.69E+09	9.46E-03	-2.02	600	--	0.48
56	Dichloromethane	75-09-2	CH ₂ Cl ₂	84.93	362	0.117	1.65E+09	3.19E-03	-2.50	16,700	1.17 x 10 ⁻⁵	1.30
57	Dichloromono-fluoromethane	75-43-4	CHCl ₂ F	102.92	1360	0.0	7.52E+09	9.21E+02	2.96	0.2	0.0	
58	1,2-Dichloropropane	78-87-5	C ₃ H ₆ Cl ₂	112.99	42	0.0782	2.55E+08	2.30E-03	-2.64	2,700	8.73E-6	2.00
59	1,3-Dichloropropane	542-75-6	C ₃ H ₄ Cl ₂	110.98	43	0.0	2.57E+08	2.33E-06	-5.63	2,700	0.0	2.00
60	1,2-Dichloro-1,1,2,2-Tetrafluoroethane	76-14-2	C ₂ Cl ₂ F ₄	170.92	--		--	2.45E-01	-0.61	137	--	2.82
61	Diethanolamine	111-42-2	C ₄ H ₁₁ NO ₂	105.14	--		--			(61)?	--	--
62	Diethyl amine	109-89-7	C ₄ H ₁₁ N	73.14	350@35C	--	1.38E+09	7.31E-03	-2.14	20,000	--	--
63	N,N-Dimethylaniline	121-69-7	C ₉ H ₁₁ N	121.18	--		--			(63)?	--	--
64	Diethyl ether	60-29-7	C ₄ H ₁₀ O	74.12	440@20C	0.0782	1.75E+09	2.65E-04	-3.58	60,400	8.61E-6	--
65	Dimethylamine	124-40-3	C ₂ H ₇ N	45.08	563 @ 0C	--	1.36E+09	5.24E-06	-5.28	--	--	-0.38
66	Dimethyl formamide	68-12-2	C ₃ H ₇ NO	73.09	4.0	0.0939	1.57E+07	1.92E-05	-4.72	20,000	1.03E-5	--
67	1,1-Dimethyl hydrazine	57-14-7	C ₂ H ₆ N ₂	60.10	157	0.1060	5.07E+08	1.24E-04	-3.91	100,000	1.09E-5	-1.32
68	2,4-Dinitrophenol	51-28-5	C ₆ H ₄ N ₂ O ₃	184.11	53.8	0.0	5.32E+08	1.53E-07	-6.82	19,500	0.0	1.50
69	1,4-Dioxane	123-91-1	C ₄ H ₈ O ₂	88.11	37	0.2290	1.75E+08	2.31E-05	-4.64	inf	1.02E-5	0.01
70	Diphenyl	92-52-4	C ₁₂ H ₁₀	154.21	--		--	1.01E-01	-1.00	7.5	--	--
71	Epichlorohydrin	106-89-8	C ₃ H ₅ ClO	92.53	17	0.0860	8.45E+07	3.23E-05	-4.49		9.08E-6	0.15
72	1,2-Epoxybutane	106-88-7	C ₄ H ₈ O	72.0	--		--			(72)?	--	--
73	Ethanol	64-17-5	C ₂ H ₆ O	46.07	50	0.1230	1.24E+08	3.03E-05	-4.52	inf	1.30E-5	-0.32
74	Ethyl acetate	141-78-6	C ₄ H ₈ O ₂	88.11	100	--	4.74E+08	1.28E-04	-3.89	79,000	--	--
75	Ethyl acrylate	140-88-5	C ₅ H ₈ O ₂	100.12	40	0.0770	2.15E+08	3.50E-04	-3.46	--	--	--

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) ^a	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (μg/m ³) ^a	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
76	Ethyl amine	75-04-7	C ₂ H ₇ N	45.08	1057		2.56E+09	5.24e-06	-5.28	inf	--	--
77	Ethylbenzene	100-41-4	C ₈ H ₁₀	106.16	10	0.0750	5.71E+07	6.44e-03	-2.19	152	7.8e-6	3.15
78	Ethyl Bromide	74-96-4	C ₂ H ₅ Br	108.97	--		--	1.00e-02	-2.00	--	--	--
79	Ethyl carbamate	51-79-6	C ₃ H ₇ NO ₂	89.09	10		4.79E+07			(79)?	--	--
80	Ethyl Chloride	75-00-3	C ₂ H ₅ Cl	64.51	1200	0.2710	4.16E+09	1.40e-02	-1.85	5,740	1.15e-5	--
81	Ethylenediamine	107-15-3	C ₂ H ₆ N ₂	60.10	10.7	--	3.46E+07	8.46e-06	-5.07	inf	--	--
82	Ethylene dibromide	106-93-4	C ₂ H ₄ Br ₂	187.88	14	0.0	1.41E+08			inf	0.0	1.76
83	Ethylene glycol	107-21-1	C ₂ H ₆ O ₂	62.07	0.13	0.1080	4.34E+05	1.03e-07	-6.99	inf	1.22e-5	--
84	Ethylene imine	151-56-4	C ₂ H ₅ N	43.07	--		--	4.54e-04	-3.34	inf	--	--
85	Ethylene oxide	75-21-8	C ₂ H ₄ O	44.06	1250	0.1040	2.96E+09	1.42e-04	-3.85	--	1.45e-5	-0.22
86	Formaldehyde	50-00-0	CH ₂ O	30.03	3500	0.1780	5.65E+09	5.76e-05	-4.24	550,000	1.98e-5	0.0
87	Formic acid	64-18-6	CH ₂ O ₂	46.03	42	0.0790	1.04E+08	7.00e-07	-6.15	inf	1.37e-6	0.54
88	Furan	110-00-9	C ₄ H ₄ O	68.08	596	0.1040	2.18E+09	5.76e-03	-2.27	10,000	1.22e-5	--
89	Glycerol	56-81-5	C ₃ H ₈ O ₃	92.09	1.60E-04	0.0	7.92E+02	1.94e-08	-7.89	10,000	0.0	--
90	N-Heptane	142-82-5	C ₇ H ₁₆	100.2	46	0.0	2.48E+08	2.02e+00	0.31	3	0.0	--
91	N-Hexane	110-54-3	C ₆ H ₁₄	86.18	150.3	0.2000	6.96E+08	0.122	-0.91	13	7.77e-6	--
92	Hydrazine	302-01-2	H ₂ N ₂	32.05	14.4	--	2.48E+07	6.66e-07	-6.18	--	--	-3.08
93	Hydrochloric acid	7647-01-0	HCl	36.46	32,450		6.36E+10			(93)?	--	--
94	Hydrogen cyanide	74-90-8	CHN	27.03	--		--	4.65e-07	-6.33	inf	--	--
95	Hydrogen sulfide	7783-06-4	H ₂ S	34.08	15,200	0.1760	2.78E+10			4,000	--	--
96	Isobutanol	78-83-1	C ₄ H ₁₀ O	74.12	10	0.0860	3.98E+07	2.20e-06	-5.66	95,000	2.20e-6	--
97	Isobutyl acetate	110-19-0	C ₆ H ₁₂ O ₂	116.16	--		--	1.64e-04	-3.79	6,300	--	--
98	Isopropyl alcohol	67-63-0	C ₃ H ₈ O	60.1	42.8	0.0980	1.38E+08	1.50e-04	-3.82	inf	1.04e-5	-0.16/0.28
99	Isopropyl amine	75-31-0	C ₃ H ₉ N	59.11	460		1.46E+09	3.58e-04	-3.45	100,000	--	--
100	Isopropylbenzene	98-82-8	C ₉ H ₁₂	120.19	10.9@40C		7.04E+07	6.59e-03	-2.18	50	--	--

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) ^a	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (μg/m ³) ^a	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
101	Methanol	67-56-1	CH ₃ O	32.04	114	0.1500	1.96E+08	2.70e-06	-5.57	inf	1.64e-5	--
102	Methyl acetate	79-20-9	C ₃ H ₆ O ₂	74.08	235	0.1040	9.36E+08	1.02e-04	-3.99	194,000	1.00e-5	--
103	Methyl acrylate	96-33-3	C ₄ H ₆ O ₂	86.09	--	--	--	1.44e-07	-6.84	60,000	--	--
104	Methyl amine	74-89-5	CH ₃ N	31.06	770@ -6C	--	1.29E+09	5.38e-03	-2.27	11,500	--	--
105	Methyl bromide	74-83-9	CH ₃ BR	94.94	--	--	--	2.21e-01	-0.66	17,500	--	--
106	Methyl-tert-butyl-ether	1634-04-4	C ₅ H ₁₂ O	88.15	245	0.0806	1.16E+09	5.92e-04	-3.23	48,000	8.026e-6	0.26
107	Methyl chloride	74-87-3	CH ₃ Cl	50.49	3830	0.1260	1.04E+10	8.14e-03	-2.09	6,360	6.5e-6	0.95
108	Methylcyclohexane	108-87-2	C ₇ H ₁₄	98.19	43	--	2.27E+08	9.79e-01	-0.01	14	--	--
109	Methyl-ethyl-ketone	78-93-3	C ₄ H ₈ O	72.11	100	0.0808	3.88E+08	2.16e-04	-3.67	275,000	0.98e-5	1.74±0.12
110	Methyl formate	107-31-3	C ₂ H ₄ O ₂	60.05	500	--	1.61E+09	1.30e-01	-0.89	304	--	--
111	Methyl hydrazine	60-34-4	CH ₃ N ₂	46.07	49.6	--	1.23E+08	3.44e-06	-5.46	inf	--	--
112	Methyl iodide	74-88-4	CH ₃ I	141.94	91	--	--	2.53e-03	-2.60	14,000	--	--
113	Methyl-Isobutyl-Ketone	108-10-1	C ₅ H ₁₀ O	100.16	19.31	0.0750	1.04E+08	4.95e-05	-4.31	19,000	7.08e-6	--
114	Methyl isocyanate	624-83-9	C ₂ H ₃ NO	57.05	348	--	1.07E+09	--	--	**	--	--
115	Methyl-Isopropyl-Ketone	563-80-4	C ₅ H ₁₀ O	86.13	15.7	0.0750	7.27E+07	4.58e-04	-3.34	47,000	0.78e-05	--
116	Methyl mercaptan	74-93-1	CH ₃ S	48.1	--	--	--	4.18e-03	-2.38	23,300	--	--
117	Methyl methacrylate	80-62-6	C ₅ H ₈ O ₂	100.10	39	0.0770	2.10E+08	6.60e-05	-4.18	15,000	8.50e-6	0.79
118	Methyl-N-Propyl-Ketone	107-87-9	C ₅ H ₁₀ O	86.13	--	--	--	4.58e-04	-3.34	--	--	--
119	Alpha-Methyl-Styrene	98-83-9	C ₉ H ₁₀	118.18	0.076	0.2640	4.83E+05	5.91e-03	-2.23	2	--	--
120	Monoethanolamine	141-43-5	C ₂ H ₇ NO	61.08	--	--	--	3.22e-07	-6.49	100,000	--	--
121	Morpholine	110-91-8	C ₄ H ₉ NO	87.12	10.08	0.0910	4.72E+07	5.73e-05	-4.24	inf	9.60e-6	-1.08
122	Naphthalene	91-20-3	C ₁₀ H ₈	128.19	0.023	0.0590	1.58E+05	4.80e-04	-3.32	30	7.50e-6	3.01/3.45
123	2-Nitropropane	79-46-9	C ₃ H ₇ NO ₂	89.09	12.9	--	6.18E+07	2.23e-04	-3.65	100,000	--	--
124	N-Nitrosodimethylamine	62-75-9	C ₂ H ₅ N ₂ O	74.08	--	--	--	3.0x10 ⁻⁸	-7.52	1.2x10 ⁷	--	--

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) ^a	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (μg/m ³) ^a	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
125	N-Nitrosomorpholine	59-89-2	C ₄ H ₈ N ₂ O ₂	116.11	—	0.0590	—			0.059	1.00e-5	—
126	N-Nonane	111-84-2	C ₉ H ₂₀	128.26	4.28		2.95E+07	4.48e-01	-0.35	79	—	—
127	N-Octane	111-65-9	C ₈ H ₁₈	114.23	17	0.0	1.04E+08	3.87e+00	0.59	20	0.0	—
128	N-Pentane	109-66-0	C ₅ H ₁₂	72.15	513		1.99E+09	1.22e-01	-0.91	360	—	—
129	Phenanthrene	85-01-8	C ₁₄ H ₁₀	178.23	2.00E-04	0.0	1.92E+03	6.05e-03	-2.22	0.82	0.0	4.46
130	Phenol	108-95-2	C ₆ H ₆ O	94.11	0.0341	0.0820	1.72E+05	4.54e-07	-6.34	80,000	9.10e-6	1.46
131	Phosgene	75-44-5	CCl ₂ O	98.92	1,394	0.1080	7.41E+09	1.71e-01	-0.767	slightly	1.12e-6	—
132	Phosphine	7803-51-2	H ₃ P	34.00	2,000	—	3.66E+09			6,200	—	—
133	Phthalic anhydride	85-44-9	C ₈ H ₄ O ₃	148.11	0.0015	0.0710	1.19E+04	9.00e-07	-6.05	153,000	8.60e-6	—
134	Propane	74-98-6	C ₃ H ₈	44.1	7600	—	1.80E+09	2.20e-02	-1.66	2,000	—	2.36
135	1,2-Propanediol	57-55-6	C ₃ H ₈ O ₂	76.11	0.3		—	1.50e-06	-5.82	20,000	—	—
136	1-Propanol	71-23-8	C ₃ H ₈ O	60.1	20.85		6.74E+07	1.50e-04	-3.82	inf	—	—
137	beta-Propiolactone	57-57-8	C ₃ H ₄ O ₂	72.06	3.4	—	1.32E+07			350,000	—	—
138	Propionaldehyde	123-38-7	C ₃ H ₆ O	58.08	300	0.102	9.37E+08	1.15e-06	-5.94	200,000	1.14e-5	—
139	Propionic acid	79-09-4	C ₃ H ₆ O ₂	74.08	10	—	3.98E+07	4.87e-05	-4.31	inf	—	—
140	N-Propyl-Acetate	109-60-4	C ₅ H ₁₀ O ₂	102.12	35	0.0	1.92E+08	2.94e-04	-3.53	20,400	0.0	—
141	Propylene oxide	75-56-9	C ₃ H ₆ O	58.08	524.5	0.1040	1.64E+09	1.34e-03	-2.87	30,000	1.00e-5	—
142	1,2-Propylenimine	75-55-8	C ₃ H ₇ N	54.1	112		3.26E+08			(142)?	—	-0.48
143	Pyridine	110-86-1	C ₅ H ₅ N	79.1	20	0.0910	8.50E+07	2.36e-05	-4.63	inf	8.10e-6	0.66
144	Quinone	106-51-4	C ₆ H ₄ O ₂	108.09	—		—			(144)?	—	—
145	Styrene	100-42-5	C ₈ H ₈	104.15	7.3	0.0710	4.09E+07	2.61e-03	-2.58	300	8.00e-6	2.95
146	1,1,1,2-Tetrachloro-2,2-Difluoroethane	76-11-9	C ₂ Cl ₄ F ₂	203.83	—		—	2.45e-01	-0.61	—	—	—
147	1,1,2,2-Tetrachloroethane	79-34-5	C ₂ H ₂ Cl ₄	167.85	6.5	0.0710	5.86E+07	2.50e-04	-3.60	2,900	7.90e-6	2.39
148	Tetrachloroethylene	127-18-4	C ₂ Cl ₄	165.83	19	0.0720	1.69E+08	2.90e-02	-1.54	150	8.2e-6	2.60*
149	Tetrahydrofuran	109-99-9	C ₄ H ₈ O	72.11	72.1	0.0980	2.79E+08	4.90e-05	-4.31	inf	1.05e-5	—

Appendix A. (Continued)

No.	Organic Compound	CAS NO.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) ^a	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc. (µg/m ³) ^a	Henry's Law Constant		Maximum Water Solubility (mg/L)	Diffusivity in Water (cm ² /sec)	Log Kow
								H ^b	Log H			
150	Toluene	108-88-3	C ₇ H ₈	92.14	30	0.0870	1.49E+08	6.68e-03	-2.18	515	8.60e-6	2.73
151	p-Toluidine	106-49-0	C ₇ H ₉ N	107.16	0.3	--	1.73E+06	1.91e-05	-4.72	7,400	--	--
152	1,1,1-Trichloroethane	71-55-6	C ₂ H ₃ Cl ₃	133.41	123	0.0780	8.82E+08	1.74e-02	-1.76	4,400	8.8e-6	2.5
153	1,1,2-Trichloroethane	79-00-5	C ₂ H ₃ Cl ₃	133.41	25	0.0792	1.79E+08	7.40e-04	-3.13	4,500	8.80e-6	2.47
154	Trichloroethylene	79-01-6	C ₂ HCl ₃	131.4	75	0.0790	5.30E+08	9.10e-03	-2.04	1,100	9.10e-6	2.38
155	Trichlorofluoromethane	75-69-4	CCl ₃ F	137.37	667	0.0870	4.92E+09	5.83e-02	-1.23	1,100	9.70e-6	2.53
156	1,2,3-Trichloropropane	96-18-4	C ₃ H ₃ Cl ₃	147.43	3.1	0.0710	2.46E+07	2.80e-02	-1.55	--	7.90e-6	--
157	1,1,2-Trichloro-1,2,2-Trifluoroethane	76-13-1	C ₂ Cl ₃ F ₃	187.38	300	0.0780	3.02E+09	2.45e-01	-0.61	170	8.20e-6	2.00
158	Triethylamine	121-44-8	C ₆ H ₁₅ N	101.19	400	--	2.18E+09	2.66e-03	-2.58	20,000	--	--
159	Trifluorobromomethane	75-63-8	CBRF ₃	148.91	--	--	--	1.00e-01	-1.00	--	--	--
160	1,2,3-Trimethylbenzene	526-73-8	C ₉ H ₁₂	120.19	--	--	--	1.47e-01	-0.83	--	--	--
161	1,2,4-Trimethylbenzene	95-63-6	C ₉ H ₁₂	120.19	--	--	--	1.47e-01	-0.83	57	--	--
162	1,3,5-Trimethylbenzene	108-67-8	C ₉ H ₁₂	120.19	1.86	--	1.20E+07	1.47e-01	-0.83	20	--	--
163	Vinyl Acetate	108-05-4	C ₄ H ₆ O ₂	86.09	115	0.0850	5.32E+08	6.20e-04	-3.21	20,000	9.20e-6	--
164	Vinyl bromide	593-60-2	C ₂ H ₃ Br	107.0	895	--	5.15E+09	--	--	(164)?	--	--
165	Vinyl Chloride	75-01-4	C ₂ H ₃ Cl	62.5	2660	0.0900	8.94E+09	8.60e-02	-1.07	1.1	1.04e-5	1.38
166	m-Xylene	108-38-3	C ₈ H ₁₀	106.2	8	0.0700	4.57E+07	5.20e-03	-2.28	200	7.80e-6	3.26
167	o-Xylene	95-47-6	C ₈ H ₁₀	106.2	7	0.0870	4.00E+07	5.27e-03	-2.28	175	1.00e-5	2.95
168	p-Xylene	106-42-3	C ₈ H ₁₀	106.2	9.5	0.0	5.42E+07	5.27e-03	-2.28	198	0.0	3.15

^a At 25°C

^b $\frac{\text{atm} \cdot \text{m}^3}{\text{g} \cdot \text{mol}}$

APPENDIX B

PHYSICAL PROPERTY DATA
FOR SELECTED SEMI-VOLATILE ORGANIC COMPOUNDS
(For compounds in Table 5 of the report)

Appendix B - Physical Property Data For Selected Semi-Volatile Organic Compounds

No.	Organic Compound	CAS No.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg)*	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc (µg/m ³)*	Henry's Law Constant		Max H ₂ O Solubility (mg/L)	Diffusivity in H ₂ O (cm ² /sec)	Log K _{ow}
								H ^b	Log H			
1	Acenaphthene	83-32-9	C12H10	154.21	0.005	0.0	4.15e+04	7.71e-08	-7.11	2	0.0	
2	2-Acetaminofluorene	53-96-3	C15H13NO	223.26	0.017		2.01e+05	2.65e-08	-7.58	6.5		3.28
3	2-Acetylfuran	1192-62-7	C6H6O2	110.11		0.0		1.10e-04	-3.96	100	0.0	
4	Benzidine	92-87-5	C12H12N2	184.24		0.0298		3.66e-07	-6.44	400		1.55
5	Benzo(a)anthracene	56-55-3	C18H12	228.30	1.50e-07	0.051	1.84e+00	1.38e-09	-8.86	0.012	9.00e-08	5.23
6	Benzo(a)pyrene	50-32-8	C20H12	252.32	0.000568	0.043	7.71e+03	1.38e-09	-8.86	0.003	9.00e-08	6.16
7	Benzo(b)fluoranthene	205-99-2	C20H12	252.32	1626	0.044	2.21e+10	2.01e-05	-4.70	0.0011	4.70e-06	6.33
8	Benzo(g,h,i)perylene	191-24-2	C22H12	276.34								
9	Benzo(k)fluoranthene	207-08-9	C20H12	252.32	3.84e-04	0.044	5.21e+03	1.06e-07	-6.98	0.0006	4.70e-06	6.46
10	Bis(2-ethylhexyl)phthalate	117-81-7	C24H38O4	390.56	2.53e-03		5.31e+04	1.38e-07	-6.86	0.35		5.61
11	Chlordane	57-74-9	C10H6Cl8	410.00	1.00e-05	0.0	2.20e+02	3.67e-05	-4.44	0.93	0.0	5.58
12	Chrysene	218-01-9	C18H12	228.30	5.76e-10	0.046	7.07e-03	1.18e-09	-8.93	0.0017	5.00e-06	4.96
13	Cresol	1319-77-3	C7H8O	108.15	0.3		1.74e+06	2.13e-05	-4.67	2000		1.95
14	Dioxin (2,3,7,8-TCDD)	1746-01-6	C12H4Cl4O2	321.96	1.94e-04		3.36e+03	4.44e-05	-4.35	1.68e-04		6.37
15	Dibenzofuran	132-64-9	C12H8O	168.21								
16	Dibenzo(a,h)anthracene	53-70-3	C22H14	278.36	5.20e-11	0.042	7.78e-04	3.81e-08	-7.42	0.0015	4.50e-06	6.85
17	Di-n-butylphthalate	84-74-2	C16H22O4	278.35	1.00e-05	0.0439	1.50e+02	2.80e-07	-6.55	400	7.80e-06	5.60
18	Ethylenamine	593-67-9										
19	Fluoranthene	206-44-0	C16H10	202.26	0.0177	0.049	1.93e+05	6.73e-02	-1.17	0.3	5.30e-06	5.00
20	Fluorene	86-73-7	C13H10	166.23	1.63e-05	0.055	1.46e+02	1.78e-08	-7.75	2	5.70e-06	4.12
21	Heptachlor	76-44-8	C10H5Cl7	373.32	0.0008	0.0	1.61e+04	2.30e-08	-7.64	0.056	0.0	5.19
22	Hexachlorocyclopentadiene	77-47-4	C5Cl6	272.77	0.081	0.0561	1.19e+06	1.60e-02	-1.80		6.16e-08	
23	Indeno(1,2,3,CD)pyrene	193-39-5	C22H12	276.34	7.60e-08	0.044	1.13e+00	5.07e-13	-12.29	0.00017	4.50e-06	7.09
24	Lindane	58-89-9	C6H6Cl6	290.83	9.40e-06		1.47e+02	3.16e-06	-5.50	12.4		3.71
25	Maleic anhydride	108-31-6	C4H2O3	98.06	0.0001	0.095	5.27e+02	4.00e-08	-7.40	788	1.11e-05	
26	2-Methylnaphthalene	91-57-6	C11H10	142.20	0.054	0.0	4.15e+05	5.80e-05	-4.24	26		

No.	Organic Compound	CAS No.	Formula	Molecular Weight (g/g-mol)	Vapor Pressure (mm Hg) ^a	Diffusivity in Air (cm ² /sec)	Saturated Vapor Conc (μg/m ³) ^a	Henry's Law Constant		Max H ₂ O Solubility (mg/L)	Diffusivity in H ₂ O (cm ² /sec)	Log K _{ow}
								H ^b	Log H			
27	p-Nitrosodiphenylamine	156-10-5	C ₁₂ H ₁₀ N ₂ O	198.23								
28	Nitrobenzene	98-95-3	C ₆ H ₅ NO ₂	123.11	0.3	0.076	1.99e+06	1.13e-05	-4.95	1950	8.60e-08	1.91
29	PCBs	1336-36-3		328.00	1.42	0.104	2.51e+07	2.94e-04	-3.53	0.0077	1.00e-05	9.21
30	PAHs	61-78-9	C ₉ H ₁₀ N ₂ O ₃	194.19								
31	Parathion	56-38-2	C ₁₀ H ₁₄ NO ₅ PS	291.27	0.003	0.0	4.70e+04	4.80e-05	-4.32	19	0.0	3.38
32	Pyrene	129-00-0	C ₁₆ H ₁₀	202.26	9.74e-04	0.051	1.06e+04	7.00e-09	-8.15	2	5.50e-06	4.88
33	Tridecane	629-50-5	C ₁₃ H ₂₈	184.37	1.55e-09		1.54e-02					
34	Undecane	1120-21-4	C ₁₁ H ₂₃	156.32	1.20e-08		1.01e-01	1.83e+00	0.26			

^a At 25°C

^b $H \left[\frac{\text{atm} \cdot \text{m}^3}{\text{g} \cdot \text{mol}} \right]$