

TECHNICAL SUPPORT DOCUMENT
FOR
THE SURFACE DISPOSAL OF SEWAGE SLUDGE

Prepared for
Office of Water
U.S. Environmental Protection Agency
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PREFACE

On November 25, 1992, pursuant to Section 405(d) of the Clean Water Act, the Administrator of the U.S Environmental Protection Agency signed a notice for publication in the *Federal Register* taking final action with respect to a regulation establishing use or disposal standards, including numerical pollutant limits, for sewage sludge. This regulation was published in the *Federal Register* on February 19, 1993 (58 *Fed. Reg.* 9248, *et seq.*).

The information included in this Technical Support Document provides further explanation of the regulation. It describes in detail the risk assessment methodology the Agency used in evaluating pollutants to determine whether they posed a risk to public health and the environment as well as the approach used to derive the risk-based numerical pollutant limits.

This document is substantially similar to the Technical Support Document that is included in the evidentiary record considered by the Administrator when promulgating the sewage sludge use or disposal regulation. However, typographical and technical errors found in the November 25, 1992, signature version relied on by the Administrator have been corrected in this Technical Support Document. A copy of an errata sheet showing where changes have been made is enclosed with this copy. The November 25, 1992, signature version of this Technical Support Document is available for review and copying at EPA's Water Docket, Room L-102, 401 M Street, S.W., Washington, D.C. 20460. For access to this and other docket materials, call (202) 260-1306.

ERRATA

TECHNICAL SUPPORT DOCUMENT FOR SURFACE DISPOSAL OF SEWAGE SLUDGE

Federal Register Version	Final Version	Difference	Explanation
Page vii. List of Units and Acronyms. The definition of D_{eth} spells diethyl as diethly.	Page vii. List of Units and Acronyms. The definition of D_{eth} spells diethyl as diethly.	No	Should have been corrected in editing, but wasn't.
Page viii. List of Units and Acronyms. In the definition for f_p , an (was added as a correction.	Page viii. List of Units and Acronyms. In the definition for f_p , the (was not added as a correction.	Yes	Correction was missed in final editing.
Page viii. List of Units and Acronyms. In the definition for f_p , impoundment should have been corrected to impoundment.	Page viii. List of Units and Acronyms. In the definition for f_p , impoundment should have been corrected to impoundment.	No	Should have been corrected in editing, but wasn't.
Page ix. List of Units and Acronyms. The definition for K_p is mass transfer coefficient for liquid layer and should read mass transfer coefficient for gas layer.	Page ix. List of Units and Acronyms. The definition for K_p is mass transfer coefficient for liquid layer and should read mass transfer coefficient for gas layer.	No	Should have been corrected in editing, but wasn't.
Page x. List of Units and Acronyms. In the definition for MTD dose is misspelled as doxe.	Page x. List of Units and Acronyms. In the definition for MTD dose is misspelled as doxe.	No	Should have been corrected in editing, but wasn't.
	Pages xiii-xiv. List of Tables. Tables 5-2 through 5-24 are on different pages from those in the FR version.	Yes	Formatting changes and editing changes which changed page numbers.
Page xiv. Table 6-2 should be titled Pollutants...Sewage Sludge (Meet One of Three Deletion Criteria) instead of TWO of Three.	Page xiv. Table 6-2 should be titled Pollutants...Sewage Sludge (Meet One of Three Deletion Criteria) instead of TWO of Three.	No	Should have been corrected in editing, but wasn't.
Pages 1-11, 4-3, 5-1, 5-56, 5-57, 5-73, 5-89, and 5-99. Ground water was corrected to ground-water.	Pages 1-11, 4-3, 5-1, 5-56, 5-57, 5-73, 5-89, and 5-99. Ground water was not corrected to ground-water.	Yes	Correction missed in final editing.

Federal Register Version	Final Version	Difference	Explanation
Page 3-3 reads For noncarcinogenic health effects...and is based on a qualitative assessment.	Page 3-3 reads For noncarcinogenic health effects...and is based only on a qualitative assessment.	Yes	Editing change to make the statement more precise.
Page 3-5 reads Most dose-response relationships are estimated based on animal studies.	Page 3-5 reads Most dose-response relationships are estimated based on results of animal studies.	Yes	Editing change to make the statement more precise.
Pages 5-80, 5-81, 5-82, 5-83, 5-84, 5-85, 5-86, and 5-87. Tables 5-2 through 5-9. The vapor pathway column has NA for many of the chemicals.	Pages 5-80, 5-81, 5-82, 5-83, 5-84, 5-85, 5-86, and 5-87. Tables 5-2 through 5-9. The vapor pathway column has #N/A instead of the original NA for many of the chemicals.	Yes	Formatting error.
Page 5-80. Table 5-2 has 78,00 and 44,00 in the groundwater pathway column for Benzene and Bis(2-ethylhexyl)phthalate, respectively.	Page 5-80 Table 5-2 has 78,00 and 44,00 in the groundwater pathway column for Benzene and Bis(2-ethylhexyl)phthalate, respectively.	No	Should have been corrected in editing, but wasn't.
Page 5-82. Table 5-4 has 2,300 in the vapor pathway column for n-Nitrosodimethylamine.	Page 5-82. Table 5-4 has 2,3000 in the vapor pathway column for n-Nitrosodimethylamine.	Yes	Error in final editing.
Page 5-83. Table 5-5 has 35,00 in the groundwater pathway column for Arsenic.	Page 5-83. Table 5-5 has 35,00 in the groundwater pathway column for Arsenic.	No	Should have been corrected in editing, but wasn't.
Page 5-93. Table 5-10 read Average Air Temperature (oK) and was corrected to read Average Air Temperature. (°K).	Page 5-93. Table 5-10 now reads Average Air Temperature (K).	Yes	Correction to degree missed.
Pages 5-115 and 5-119 contain Tables 5-18 and 5-21, respectively.	Tables 5-18 and 5-21 now are contained on pages 5-114 and 5-120, respectively.	Yes	Formatting change.
Page 5-116. Table 5-19. Lindane is inserted after DDT.	Page 5-116. Table 5-19. Lindane is inserted before DDT.	Yes	Correction error in final editing.
	Section 10. References. Many of the references have changed pages.	Yes.	Insertion of missing references and change of top and bottom margins.

CONTENTS

PAGE

LIST OF UNITS AND ACRONYMS vi
LIST OF TABLES xiii

SECTION ONE INTRODUCTION 1-1

1.1	Background	1-1
1.2	Description of Part 503	1-3
1.2.1	General Provisions	1-3
1.2.1.1	Purpose and Applicability	1-3
1.2.1.2	Compliance Period	1-4
1.2.1.3	Permits and Direct Enforceability	1-5
1.2.1.4	Relationship to Other Regulations	1-5
1.2.1.5	Additional or More Stringent Requirements	1-6
1.2.1.6	Exclusions	1-6
1.2.1.7	Requirement for a Person Who Prepares Sewage Sludge	1-7
1.2.1.8	Sampling and Analysis	1-7
1.2.1.9	General and Special Definitions	1-7
1.2.2	Subpart C—503 Standard and Other Requirements	1-8
1.2.2.1	General Requirements	1-8
1.2.2.2	Pollutant Limits	1-9
1.2.2.3	Operational Standard	1-10
1.2.2.4	Management Practices	1-10
1.2.2.5	Other Requirements (Frequency of Monitoring, Recordkeeping, and Reporting)	1-11
1.3	Scope of the Sewage Sludge Surface Disposal Technical Support Document	1-13

SECTION TWO SURFACE DISPOSAL OF SEWAGE SLUDGE 2-1

2.1	Introduction	2-1
2.2	Exclusions	2-1
2.3	Types of Surface Disposal Sites	2-2
2.3.1	Monofills	2-2
2.3.2	Surface Impoundments	2-4
2.3.3	Dedicated Sites	2-4

SECTION THREE RISK ASSESSMENT METHODOLOGY 3-1

3.1	Hazard Identification	3-1
3.2	Dose-Response Evaluation	3-5
3.3	Exposure Evaluation	3-7
3.3.1	Monitoring	3-7
3.3.2	Modeling	3-8

CONTENTS (cont.)

	<u>PAGE</u>
3.3.3 Population Analysis	3-9
3.4 Risk Characterization	3-9
 SECTION FOUR POLLUTANTS AND PATHWAYS OF CONCERN FOR PART 503 RISK ASSESSMENT FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE	
4.1 Initial List of Pollutants	4-1
4.2 Environmental Profiles and Hazard Indices	4-3
 SECTION FIVE PART 503 RISK ASSESSMENT METHODOLOGY FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE	
5.1 Description of Two Model Prototypes of Surface Disposal Sites—Monofill and Surface Impoundment	5-1
5.2 General Approach Used to Derive Risk-Based Pollutant Criteria	5-3
5.2.1 Mass Balance	5-4
5.2.2 Modeling of Ground-Water Contamination	5-4
5.2.3 Modeling the Contamination of Ambient Air	5-5
5.2.4 Exposure Scenarios	5-6
5.2.5 Uncertainties and Limitations	5-7
5.3 Risk Assessment Methodology for Monofill Prototype	5-7
5.3.1 Methodology for Mass Balance	5-8
5.3.1.1 Pollutant Losses through Leaching	5-8
5.3.1.2 Pollutant Losses to Volatilization	5-9
5.3.2 Methodology for Ground Water Pathway	5-15
5.3.2.1 Simulating Flow and Pollutant Transport through Unsaturated and Saturated Soil Zones	5-16
5.3.3 Methodology for Vapor Pathway	5-21
5.3.4 Monofill Prototype Sample Calculations for Pollutant Criteria	5-26
5.3.4.1 Mass Balance Calculations	5-26
5.3.4.1.1 Pollutant Losses through Leaching	5-26
5.3.4.1.2 Pollutant Losses through Volatilization	5-27
5.3.4.2 Pollutant Criteria Calculations for Ground-Water Pathway	5-35
5.3.4.3 Pollutant Criteria Calculations for Vapor Pathway	5-39
5.4 Risk Assessment Methodology for Surface Impoundment Prototype	5-42
5.4.1 Methodology for Mass Balance	5-42
5.4.1.1 Pollutant Losses from Liquid Layer	5-44
5.4.1.2 Pollutant Losses from Sediment Layer	5-51
5.4.2 Methodology for the Ground-Water Pathway	5-54
5.4.3 Methodology for Vapor Pathway	5-60
5.4.4 Surface Impoundment Prototype Sample Calculations for Pollutant Criteria	5-63

CONTENTS (cont.)

	<u>PAGE</u>
5.4.4.1 Mass Balance Calculations	5-63
5.4.4.2 Pollutant Criteria Calculations for Ground-Water Pathway	5-73
5.4.4.3 Pollutant Criteria Calculations for Vapor Pathway	5-76
5.5 Results of Part 503 Risk Assessment	5-79
5.6 Factors Related to Risk Assessment	5-79
5.6.1 The Highly Exposed Individual	5-88
5.6.2 Factors Related to Calculating the Human Dose	5-89
5.6.2.1 Maximum Pollutant Level	5-89
5.6.2.2 Cancer Potency	5-89
5.6.2.3 Risk Level	5-90
5.6.2.4 Relative Effectiveness of Exposure	5-91
5.6.2.5 Duration of Exposure	5-91
5.6.2.6 Body Weight	5-91
5.6.2.7 Inhalation Rate	5-92
5.7 Technical Parameters Used to Derive Risk-Based Pollutant Criteria—Tables ..	5-92
5.8 Technical Parameters Used to Derive Risk-Based Pollutant Criteria— Discussion	5-92
5.8.1 Site Parameters	5-98
5.8.1.1 Area of the Disposal Site	5-98
5.8.1.2 Depth of Disposal Facility	5-98
5.8.1.3 Distance to Well	5-99
5.8.1.4 Thickness of Cover	5-99
5.8.1.5 Numbers of Days Average Cell Uncovered	5-99
5.8.1.6 Inflow Rate	5-100
5.8.1.7 Ratio of Sludge Volume to Total Volume	5-100
5.8.1.8 Site Life	5-101
5.8.1.9 Wind Velocity	5-101
5.8.1.10 Air Temperature	5-101
5.8.2 Sludge Parameters	5-102
5.8.2.1 Solids Contact	5-102
5.8.2.2 Particle Density of Sludge	5-103
5.8.3 Soil Parameters	5-103
5.8.3.1 Soil Type	5-103
5.8.3.2 Porosity of Sludge/Soil	5-104
5.8.3.3 Bulk Density of Soil	5-105
5.8.3.4 Porosity of Cover Soil	5-105
5.8.3.5 Saturated Hydraulic Conductivity of Soil	5-105
5.8.3.6 Unsaturated Hydraulic Conductivity of Soil	5-106
5.8.3.7 Fraction of Organic Carbon in Soil or Sludge	5-106
5.8.3.8 Depth to Ground Water	5-107
5.8.4 Hydrologic Parameters	5-107
5.8.4.1 Net Recharge or Seepage	5-108
5.8.4.2 Thickness of Aquifer	5-108
5.8.4.3 Hydraulic Gradient	5-110
5.8.5 Chemical-Specific Parameters	5-110
5.8.5.1 Distribution Coefficients	5-110

CONTENTS (cont.)

	<u>PAGE</u>
5.8.5.2 Decay Rates	5-114
5.8.5.3 Molecular Weight	5-117
5.8.5.4 Henry's Law Constants	5-117
5.8.5.5 Diffusion Coefficients	5-121
5.8.5.6 Reference Water Concentration	5-121
5.8.5.7 Reference Air Concentration	5-123
SECTION SIX	
POLLUTANT LIMITS FOR SEWAGE SLUDGE PLACED ON A SURFACE DISPOSAL SITE	6-1
6.1 Pollutant Selection Process	6-1
6.2 Derivation of Pollutant Concentration Limits	6-2
SECTION SEVEN	
MANAGEMENT PRACTICES	7-1
7.1 Protection of Threatened or Endangered Species	7-1
7.2 Restriction of Base Flood Flow	7-1
7.3 Geological Stability	7-1
7.3.1 Seismic Impact Zones	7-2
7.3.2 Fault Areas	7-2
7.3.3 Unstable Areas	7-2
7.4 Protection of Wetlands	7-3
7.5 Collection of Runoff	7-3
7.6 Collection of Leachate	7-3
7.7 Limitations on Methane Gas Concentrations	7-4
7.8 Prohibition on Crop Production	7-5
7.9 Prohibition on Grazing	7-5
7.10 Restriction of Public Access	7-6
7.11 Protection of Ground Water	7-6
SECTION EIGHT	
PATHOGEN AND VECTOR ATTRACTION REDUCTION REQUIREMENTS	8-1
8.1 Pathogen Requirements	8-1
8.2 Vector Attraction Reduction	8-2

CONTENTS (cont.)

	<u>PAGE</u>
SECTION NINE	
FREQUENCY OF MONITORING, RECORDKEEPING, AND REPORTING REQUIREMENTS	9-1
9.1 Frequency of Monitoring	9-1
9.1.1 Sewage Sludge (Other Than Domestic Septage)	9-1
9.1.2 Domestic Septage	9-3
9.1.3 Air Monitoring for Methane Gas	9-3
9.2 Recordkeeping	9-3
9.2.1 Sewage Sludge (Other Than Domestic Septage)	9-4
9.2.2 Domestic Septage	9-4
9.3 Reporting Requirements	9-5
 SECTION TEN	
REFERENCES	10-1
 APPENDIX A	
STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE	A-1
Subpart A—General Provisions	
Subpart C—Surface Disposal	
Subpart D—Pathogens and Vector Attraction Reduction	
 APPENDIX B	
PARTITIONING OF CONTAMINANT AMONG AIR, WATER, AND SOLIDS IN SOIL	B-1
 APPENDIX C	
DERIVATION OF FIRST-ORDER COEFFICIENT FOR LOSSES TO LEACHING	C-1
 APPENDIX D	
DERIVING A "SQUARE WAVE" FOR THE MONOFILL PROTOTYPE	D-1
 APPENDIX E	
JUSTIFICATION FOR THE DELETION OF POLLUTANTS FROM THE FINAL STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE	E-1
 APPENDIX F	
CALCULATION OF THE AMOUNT OF SEWAGE SLUDGE USED OR DISPOSED FOR THE PART 503 FREQUENCY OF MONITORING REQUIREMENTS	F-1

LIST OF UNITS AND ACRONYMS

α	=	van Genuchten water retention parameter
α_i	=	intermediate variable used to calculate emissions from contaminated soil
α_l	=	longitudinal dispersivity (m)
β	=	van Genuchten water retention parameter soil
θ	=	angle subtended by width of disposal site at distance equal to estimated virtual distance from site (degrees)
θ_a	=	air-filled porosity (dimensionless)
θ_{cm}	=	air-filled porosity in cover layer of soil (dimensionless)
θ_{ct}	=	total porosity in cover layer of soil (dimensionless)
θ_e	=	effective porosity of soil (dimensionless)
θ_r	=	van Genuchten water retention parameter
θ_t	=	total porosity (dimensionless)
θ_w	=	water-filled porosity (dimensionless)
μ_a	=	viscosity of air (g/cm-sec)
μ_w	=	viscosity of water (g/cm-sec)
ρ_a	=	density of air (g/cm ³)
ρ_d	=	particle density of sludge (kg/m ³)
ρ_{so}	=	particle density of soil (kg/m ³)
ρ_{ss}	=	particle density of sludge-soil mixture (kg/m ³)
ρ_w	=	density of water (g/cm ³ or kg/L)
σ_z	=	standard deviation of the vertical distribution of contaminant in ambient air (m)
v	=	wind speed (m/sec)
v^*	=	friction velocity of wind (m/sec)
v_{10}	=	wind velocity at 10 meters altitude (m/sec)
τ	=	empirically derived exponent (dimensionless)
ϕ	=	effective porosity (dimensionless)
ψ	=	pressure head (m)
ψ_a	=	air pressure head (m)
a	=	first coefficient for calculating σ_z
A	=	surface area of surface disposal facility (m ²)
ADF	=	anti-dilution factor (dimensionless)
ADLE	=	average daily lifetime exposure
AF	=	absorption factor
AL	=	annual loading of pollutant to monofill facility (kg/ha-yr)
b	=	second coefficient for calculating σ_z
BD	=	bulk density of sludge/soil mix (kg/m ³)
BI_j	=	background intake of pollutant j (mg/kg/day)
BW	=	average body weight (kg)
C	=	concentration of contaminant in sludge (mg/kg)
C_1	=	concentration of contaminant in liquid layer of surface impoundment (kg/m ³)
C_2	=	concentration of contaminant in sediment layer of surface impoundment (kg/m ³)

List of Units and Acronyms (cont.)

C_a	=	concentration of contaminant in air-filled pore space of sludge/soil mixture (kg/m^3)
C_{air}	=	average concentration of contaminant in ambient air at the receptor location ($\mu\text{g/m}^3$)
C_b	=	background concentration of contaminant in groundwater (mg/l)
C_i	=	concentration of contaminant in inflow to surface impoundment (kg/m^3)
C_j	=	concentration of contaminant j in sludge (g/DMT)
C_{lec}	=	concentration of contaminant in water leaching from site (kg/m^3)
C_o	=	concentration of contaminant in outflow from surface impoundment (kg/m^3)
C_s	=	concentration of contaminant adsorbed to solids (kg/kg)
C_{sod}	=	dry weight concentration of contaminant in eroded soil (mg/kg)
C_{sep}	=	concentration of contaminant in seepage from surface impoundment (mg/l)
C_{ssa}	=	the concentration of contaminant in soil eroding from the sludge management area (mg/kg)
C_t	=	total concentration of contaminant in sludge/soil mixture (kg/m^3)
C_u	=	concentration of contaminant in unsaturated zone (g/m^3)
C_w	=	concentration of contaminant in water-filled pore space of sludge/soil mixture (kg/m^3)
C_{wel}	=	concentration of contaminant in well-water (mg/L)
CI	=	incremental cancer risk for exposed individual (incremental risk of developing cancer per lifetime of exposure)
CI_j	=	incremental cancer risk from contaminant j for exposed individual (incremental risk of developing cancer per lifetime of exposure)
CWA	=	Clean Water Act
CR	=	contact rate
d_1	=	depth of liquid layer in surface impoundment (m)
d_2	=	depth of sediment layer in surface impoundment (m)
d_a	=	depth of aquifer (m)
d_c	=	depth of soil cover (m)
d_{mf}	=	depth of monofill (m)
d_{tot}	=	total depth of surface impoundment (m)
D	=	lifetime dose (mg)
D_i	=	lifetime dose to exposure group i (mg)
D^*	=	effective molecular diffusion coefficient (m^2/sec)
D_{af}	=	anti-dilution factor (unitless)
D_{a}	=	diffusivity of contaminant in air (cm^2/sec)
D_{ow}	=	diffusivity of contaminant in water (cm^2/sec)
D_{eth}	=	diffusivity of diethyl ether in water (cm^2/sec)
D_{ip}	=	dispersion coefficient for cell i from facility p ($\mu\text{g/m}^3$ per g/sec)
DF	=	dilution factor (dimensionless)
DV	=	rate of change of volume, positive for sediment layer in surface impoundment, negative for liquid layer (m^3/sec)
ED	=	exposure duration
EPA	=	Environmental Protection Agency
f_{ac}	=	fraction of total contaminant loading lost during active operation of monofill facility (dimensionless)

List of Units and Acronyms (cont.)

f_{act}	=	fraction of contaminant lost during surface impoundment's active phase (dimensionless)
f_{co}	=	fraction of facility's active lifetime that typical cell contains sludge and temporary soil cover (dimensionless)
f_{d1}	=	fraction of contaminant in the liquid layer of surface impoundment that is dissolved (dimensionless)
f_{d2}	=	fraction of contaminant in the sediment layer of surface impoundment that is dissolved (dimensionless)
f_{da}	=	fraction of contaminant loss during monofill's active lifetime that is lost to degradation (dimensionless)
f_{deg}	=	fraction of contaminant loss caused by degradation (dimensionless)
f_{deg1}	=	fraction of contaminant loss from liquid layer that is lost to degradation (dimensionless)
f_{deg2}	=	fraction of contaminant loss from sediment layer that is lost to degradation (dimensionless)
f_{del1}	=	fraction of contaminant loss from the liquid layer that is displaced by the accumulating sediment layer (dimensionless)
f_{del2}	=	fraction of contaminant entering the sediment layer that is trapped in the accumulating sediment layer (dimensionless)
f_{di}	=	fraction of contaminant loss from inactive monofill that is lost to degradation (dimensionless)
f_{la}	=	fraction of contaminant loss during monofill's active lifetime that is lost to leaching (dimensionless)
f_{lec}	=	fraction of total contaminant loss caused by leaching (dimensionless)
f_{li}	=	fraction of contaminant loss from inactive monofill that is lost to leaching (dimensionless)
f_{ls}	=	fraction of total cumulative loading lost in human lifetime (dimensionless)
f_{oc}	=	organic carbon as fraction of soil mass (dimensionless)
f_{out}	=	fraction of total contaminant loss attributable to effluent (dimensionless)
f_{out1}	=	fraction of contaminant loss from a surface impoundment that is lost to outflow (dimensionless)
f_{p1}	=	fraction of contaminant in liquid layer of surface impoundment adhering to solid particles (dimensionless)
f_{p2}	=	fraction of contaminant in sediment layer of surface impoundment adhering to solid particles (dimensionless)
f_{sep}	=	fraction of total contaminant loss attributable to seepage (dimensionless)
f_{sep1}	=	fraction of mass lost from the liquid layer of surface impoundment that is lost to seepage (dimensionless)
f_{sep2}	=	fraction of mass entering the sediment layer of surface impoundment that is lost to seepage (dimensionless)
f_{sl}	=	fraction of monofill's total volume containing pure sludge (m^3/m^3 or dimensionless)
f_{sol}	=	fraction of solids in sludge (kg/kg or dimensionless)
f_{un}	=	fraction of monofill's active lifetime that typical cell contains uncovered sludge (dimensionless)

List of Units and Acronyms (cont.)

f_{va}	=	fraction of contaminant loss during monofill's active lifetime that is lost to volatilization (dimensionless)
f_{vi}	=	fraction of contaminant loss from inactive monofill that is lost to volatilization (dimensionless)
f_{vib}	=	fraction of total contaminant loading to monofill that is lost to volatilization during a time interval equivalent to the life expectancy of the highly exposed individual (dimensionless)
f_{vol}	=	fraction of total contaminant loss caused by volatilization (dimensionless)
f_{vol1}	=	fraction of contaminant leaving the liquid layer that leaves through volatilization (dimensionless)
f_{wel}	=	ratio of contaminant concentration in well-water to concentration in seepage beneath the surface disposal facility (dimensionless)
F_s	=	volume of fluid passing through a vertical cross section of the aquifer oriented perpendicular to the direction of flow, and having a width equal to the source width and a depth equal to the saturated thickness of the aquifer (m^3/sec)
FA_1	=	annual flux of contaminant leaching from monofill (kg/ha-yr)
FD	=	ratio of effective diameter to depth of surface impoundment (dimensionless)
H	=	Henry's Law constant ($m^3\text{-atm/mol}$)
\bar{H}	=	Henry's Law constant (dimensionless at specified temperature)
i	=	index for crops
I_a	=	inhalation volume (m^3/day)
L_w	=	rate of water ingestion (l/day)
IRIS	=	Integrated Risk Information System
j	=	index for contaminants
k_{rw}	=	effective permeability (dimensionless)
K	=	saturated hydraulic conductivity (m/sec)
K_{deg}	=	degradation rate coefficient for monofill (yr^{-1})
K_{deg1}	=	degradation rate coefficient for liquid layer of surface impoundment (m^3/sec)
K_{deg2}	=	degradation rate coefficient for sediment layer of surface impoundment (m^3/sec)
K_{deg3}	=	degradation rate coefficient for unsaturated soil zone (s^{-1})
K_{del1}	=	rate coefficient for loss of contaminant from liquid layer as result of decreasing volume (m^3/sec)
K_{dis2}	=	rate coefficient for dissolved contaminant gained in sediment layer as result of increasing volume (m^3/sec)
K_s	=	mass transfer coefficient for liquid layer (m/sec)
K_l	=	mass transfer coefficient for liquid layer (m/sec)
K_{lec}	=	rate coefficient for loss of contaminant to leaching from monofill (yr^{-1})
K_{out1}	=	rate coefficient for loss of contaminant from liquid layer through outflow (m^3/sec)
K_{sep1}	=	rate coefficient for loss of contaminant through seepage from the liquid layer (m^3/sec)
K_{sep2}	=	rate coefficient for loss of contaminant through seepage from the sediment layer (m^3/sec)

List of Units and Acronyms (cont.)

K_a	=	rate coefficient for total loss of contaminant during monofill's active lifetime (yr^{-1})
K_{di}	=	rate coefficient for total loss of contaminant from inactive monofill (yr^{-1})
K_{tot}	=	lumped rate coefficient for contaminant loss from treated land (yr^{-1})
K_{tot1}	=	lumped rate coefficient for contaminant loss from the liquid layer of surface impoundment (m^3/sec)
K_{tot2}	=	lumped rate coefficient for contaminant loss from the sediment layer of surface impoundment (m^3/sec)
K_{va}	=	rate coefficient for loss of contaminant to volatilization from active monofill (yr^{-1})
K_{vi}	=	rate coefficient for loss of contaminant to volatilization from inactive monofill (yr^{-1})
K_{vol}	=	rate coefficient for loss of contaminant to volatilization from treated land (yr^{-1})
K_{vol1}	=	rate coefficient for loss of contaminant to volatilization from the liquid layer of surface impoundment (m^3/sec)
KD	=	equilibrium partition coefficient for contaminant (m^3/kg)
KOC	=	organic carbon partition coefficient (m^3/kg)
KOW	=	octanol-water partition coefficient for contaminant
LC_{50}	=	lethal dose, the average inhalation dose at which 50 percent of the animals exposed died; also used for aquatic toxicity tests, refers to the concentration of the test substance in the water that results in 50 percent mortality in the test species
LD_{50}	=	lethal dose, the average dose level that is lethal to 50 percent of the test animals, refers to oral doses
LF	=	active lifetime of monofill facility: the period in which the facility accepts sludge (yr)
LOAEL	=	Lowest Observed Adverse Effect Level
LOEL	=	Lowest Observed Effect Level
LS	=	lifespan of average individual (yr)
M_a	=	mass of air per volume of soil
M_{ga}	=	mass of gaseous contaminant per volume of soil
M_{sa}	=	mass of adsorbed contaminant per volume of soil
M_{ta}	=	total mass of contaminant per volume of soil
M_{lw}	=	mass of dissolved contaminant per volume of soil
M_s	=	mass of solids per volume of soil
M_w	=	mass of liquid per volume of soil
MGD	=	million gallons per day
MCL	=	Maximum Contaminant Level for drinking water (mg/l)
MS	=	mass of solids in one m^3 of pure sludge (kg/m^3)
MTD	=	Maximum Tolerated Dose, largest dose a test animal can receive for most of its lifetime without demonstrating adverse effects other than cancer
MW	=	molecular weight of contaminant
n	=	empirically derived exponent (dimensionless)
NAS	=	National Academy of Sciences
NOAEL	=	No Observed Adverse Effect Level
NR	=	net recharge (m/yr)

List of Units and Acronyms (cont.)

NSSS	=	National Sewage Sludge Survey
OST	=	Office of Science and Technology (EPA)
OWRS	=	Office of Water Regulations and Standards (EPA)
P_1	=	percent solids in liquid layer of surface impoundment (kg/kg)
P_2	=	percent solids in sediment layer of surface impoundment (kg/kg)
P_f	=	ratio of contaminant concentration in fillet to whole fish (unitless)
P_i	=	number of persons in cell i exceeding RfD for pollutant j (persons)
P_l	=	percent liquid in the water column of surface water body (kg/kg, or dimensionless)
P_s	=	percent solids in the water column (kg/kg or dimensionless)
PCB	=	polychlorinated biphenyl
PFRP	=	Process to Further Reduce Pathogens
POTW	=	publicly owned treatment works
PSRP	=	Process to Significantly Reduce Pathogens
q_i	=	human cancer potency for pollutant j (mg/kg/day) ⁻¹
q_1	=	human cancer potency (mg/kg-day) ⁻¹
q_{lc}	=	time-weighted average rate of contaminant volatilization from a monofill (g/m ² -sec)
q_{∞}	=	rate of contaminant volatilization from a covered monofill cell (g/m ² -sec)
q_{ua}	=	rate of contaminant volatilization from an uncovered monofill cell (g/m ² /sec)
Q_i	=	rate of inflow for sludge into a surface impoundment (m ³ /sec)
Q_o	=	rate of outflow from a surface impoundment (m ³ /sec)
Q_{sep}	=	seepage rate for both liquid and sediment layers (m/sec)
r'	=	distance from center of sludge disposal facility to HEI's location (m)
R	=	universal gas constant (m ³ -atm/mol-K)
R_{fp}	=	combined removal efficiency for pollutant j for furnace and control p expressed as fraction of original contaminant remaining in emissions (dimensionless)
RC_{air}	=	reference concentration for pollutant in air (μg/m ³)
RC_{gw}	=	reference concentration for pollutant in groundwater (kg/m ³)
RC_{loc}	=	reference concentration for pollutant in leachate from sludge monofill (kg/m ³)
RC_{sep}	=	reference concentration for pollutant in seepage from surface impoundment (kg/m ³)
RCRA	=	Resource Conservation and Recovery Act
RCS	=	reference concentration of pollutant in sewage sludge (mg/kg dry weight)
RE	=	relative effectiveness of exposure (dimensionless)
RfC	=	Reference Concentration (inhalation exposure), threshold level for critical noncancer effects below which a significant risk of adverse effects is not expected
RfD	=	Reference Dose (oral Exposure), threshold level for critical noncancer effects below which a significant risk of adverse effects is not expected
RF	=	retardation factor (dimensionless)
RF_{air}	=	reference annual flux of contaminant to air above the site (kg/ha-yr)
RF_{sw}	=	reference annual flux of pollutant to the unsaturated soil zone beneath the surface disposal facility (kg/ha-yr)

List of Units and Acronyms (cont.)

RfD_j	=	Risk Reference Dose for pollutant j (mg/kg/day)
RL	=	risk level (incremental risk of cancer per lifetime)
RWC	=	reference water concentration (mg/L)
S	=	intermediate variable used to calculate volatile emissions from soil
S_1	=	solids concentration in the liquid layer of a surface impoundment (kg/m ³)
S_2	=	solids concentration in the sediment layer of a surface impoundment (kg/m ³)
S_e	=	effective water saturation (dimensionless)
S_s	=	specific storage (m ⁻¹)
S_w	=	water saturation (dimensionless)
S_{wr}	=	residual water saturation (dimensionless)
Sc_g	=	Schmidt number on gas side (dimensionless)
Sc_l	=	Schmidt number on liquid side (dimensionless)
SC	=	mass of sludge contained in one hectare of surface disposal facility (kg/ha)
SOUR	=	specific oxygen uptake rate
SRAB	=	Sludge Risk Assessment Branch (EPA)
SRR	=	source-receptor ratio (s/m)
t	=	time (sec)
t_{na}	=	time that typical monofill cell contains sludge without soil cover (yr)
T	=	temperature (K)
TF	=	active lifetime of surface disposal facility (sec)
TP	=	length of "square wave" in which maximum total loss rate of contaminant depletes total mass of contaminant at site (sec or yr)
TSCA	=	Toxic Substances Control Act
TSS	=	total suspended solids content of the stream (mg/L)
TWIDS	=	treatment works treating domestic sewage
v	=	vertical term for dispersion of contaminant in air (dimensionless)
v_d	=	darcy velocity (m/s)
v_h	=	regional velocity of horizontal groundwater flow (m/sec)
v_i	=	superimposed radial velocity from water seeping from the impoundment (m/sec)
v_v	=	vertical velocity due to the source (m/sec)
V_a	=	volume of air in soil (m ³)
V_t	=	total volume of soil (m ³)
V_v	=	volume of void space in soil (m ³)
V_w	=	volume of water in soil (m ³)
x	=	distance from surface disposal facility to receptor (km)
x_y	=	lateral virtual distance to receptor location (m)
z	=	vertical coordinate in unsaturated zone (m)

LIST OF TABLES

	<u>Page</u>
4-1 Pollutants Selected for Environmental Profiles/ Hazard Indices	4-4
4-2 Pollutants Excluded or Deferred from Regulatory Consideration for the Surface Disposal of Sewage Sludge	4-8
4-3 Pollutants Evaluated for Surface Disposal of Sewage Sludge for the Proposed Part 503 Risk Assessment	4-9
5-1 Parameters Used to Calculate	5-24
5-2 Pollutant Loading Criteria for Sewage Sludge Disposal in Unlined Monofill Over Class I Ground Water	5-80
5-3 Pollutant Loading Criteria for Sewage Sludge Disposal in Unlined Surface Impoundment Over Class I Ground Water	5-81
5-4 Pollutant Loading Criteria for Sewage Sludge Disposal in Lined Monofill Over Class 1 Ground Water	5-82
5-5 Pollutant Loading Criteria for Sewage Sludge Disposal in Lined Surface Impoundment Over Class 1 Ground Water	5-83
5-6 Pollutant Loading Criteria for Sewage Sludge Disposal in Unlined Monofill Over Class II/III Ground Water	5-84
5-7 Pollutant Loading Criteria for Sewage Sludge Disposal in Unlined Surface Impoundment Over Class II/III Ground Water	5-85
5-8 Pollutant Loading Criteria for Sewage Sludge Disposal in Lined Monofill Over Class II/III Ground Water	5-86
5-9 Pollutant Loading Criteria for Sewage Sludge Disposal in Lined Surface Impoundment Over Class II/III Ground Water	5-87
5-10 Site and Sewage Sludge Parameters for Monofill and Surface Impoundment Prototypes	5-93
5-11 Soil and Hydrologic Parameters for Monofill and Surface Impoundment Prototypes	5-94

LIST OF TABLES (cont.)

	<u>Page</u>
5-12 Input Parameters for Vadofit Simulation of Flow and Pollutant Transport Through the Unsaturated Zone for Monofill and Surface Impoundment Prototypes	5-95
5-13 Input Parameters for AT123D Simulation of Flow and Pollutant Transport Through the Saturated Zone for Monofill Prototype	5-96
5-14 Input Parameters for AT123D Simulation of Flow and Pollutant Transport Through the Saturated Zone for the Surface Impoundment Prototype	5-97
5-15 Summary of Measured Seepage Rate from Municipal Lagoon Systems	5-109
5-16 Distribution Coefficients for Organic and Inorganic Contaminants	5-111
5-17 Octanol-Water and Organic Carbon Partition Coefficients for Organic Contaminants	5-113
5-18 Octanol-Water Partition Coefficients for PCBS	5-114
5-19 Degradation Rates	5-116
5-20 Molecular Weights for Organic Contaminants	5-118
5-21 Henry's Law Constants	5-120
5-22 Diffusion Coefficients for Organic Contaminants	5-122
5-23 Adjusted Reference Water Concentration	5-124
5-24 Human Cancer Potencies and Reference Air Concentrations	5-125
6-1 Pollutants Deleted from Regulatory Consideration-for the Surface Disposal of Sewage Sludge (Meet Two of Three Deletion Criteria)	6-3
6-2 Pollutants Deleted from Regulatory Consideration for the Surface Disposal of Sewage Sludge (Meet Two of Three Deletion Criteria)	6-4

LIST OF TABLES (cont.)

	<u>Page</u>
6-3 Pollutants Regulated by the Part 503 Regulation for the Surface Disposal of Sewage Sludge	6-5
6-4 Summary of Risk Assessment Results for Arsenic, Chromium and Nickel for Sewage Sludge Disposal in a Lined and Unlined Monofill and Surface Impoundment Over Class II/III Ground Water	6-7
6-5 Pollutant Concentrations - Active Sewage Sludge Unit Without a Liner and Leachate Collection System that Has a Unit Boundary to Property Line Distance Less Than 150 Meters	6-8
9-1 Minimum Frequency of Monitoring for Surface Disposal of Sewage Sludge	9-2

SECTION ONE

INTRODUCTION

1.1 BACKGROUND

Sewage treatment works generate sewage sludge from raw sewage in the process of maintaining the quality of our water resources. The sewage sludge must then be disposed or used in a manner that does not adversely affect public health or the environment. Sewage sludge is used or disposed in a number of ways, including land application, surface disposal, incineration, and codisposal with municipal solid waste. This document discusses the surface disposal of sewage sludge.

EPA's role is to control the potential adverse effects to public health and the environment that any use or disposal of sewage sludge may cause. Existing federal regulations are authorized under several legislative mandates and have been developed independently along media-specific concerns to regulate sewage sludge use and disposal. Section 405(d) of the Clean Water Act (CWA), as amended (33 U.S.C. 1345), directed the Agency to develop, propose, and promulgate regulations establishing standards for the use and disposal of sewage sludge. Additional authorizing legislation includes sections of the Clean Air Act, the Resource Conservation and Recovery Act (RCRA), and the Toxic Substances Control Act (TSCA).

In 1979, EPA responded to these mandates and promulgated criteria for using nonhazardous solid waste including sewage sludge when it is applied to land or disposed in landfills. These criteria were incorporated into 40 CFR Part 257, Criteria for Classification of Solid Waste Disposal Facilities and Practices, which contained specific requirements for managing sewage sludge. Any use or disposal of sewage sludge that caused the concentration of 10 heavy metals and 6 organic chemicals in an underground drinking water source to exceed specified maximum contaminant levels (MCLs) was prohibited. Management standards for using or disposing sewage sludge were set so that surface waters, flood plains, and endangered species were protected. Part 257 also established annual and cumulative application rates for cadmium,

a numerical concentration of polychlorinated biphenyls (PCBs) in sewage sludge, and pathogen requirements for sewage sludge applied to land used for the production of animal feed or food-chain crops. (Part 257 has been modified and now excludes from coverage sewage sludge applied to land.)

In 1982, the EPA established an Intra-Agency Sludge Task Force to recommend procedures for putting into effect a comprehensive regulatory program for sewage sludge management. The task force recommended that such a regulatory program be developed using the combined authorities of Section 405 of the CWA and other existing regulations so that comprehensive coverage could be provided. Accordingly, a regulation was recommended that would provide technical criteria for the use or disposal of sewage sludge.

The Office of Water Enforcement and Compliance proposed State Sludge Management Program Regulations (U.S. EPA, 1986a). These regulations proposed that states develop management programs that comply with existing federal criteria for the use or disposal of sewage sludge. The proposed State Sludge Management Program Regulations focused on the procedural requirements for submittal, review, and approval of state sewage sludge management programs. On March 9, 1988, these regulations were proposed again to reflect changes in requirements for sewage sludge management programs imposed by the 1987 Water Quality Act. After public comment, these regulations were promulgated under 40 CFR Part 501 on May 2, 1989.

Although EPA's Office of Solid Waste began the task of preparing a comprehensive sewage sludge regulation in 1979 with the promulgation of 40 CFR Part 257, the overall task of completing the comprehensive sewage sludge regulation was transferred to the Office of Water in 1984. A Wastewater Solids Criteria Branch was established under the Office of Water Regulations and Standards (OWRS) within the Office of Water to develop the risk assessment to support the rule. After the Office of Water was reorganized, the OWRS was renamed the Office of Science and Technology (OST), and the Wastewater Solids Criteria Branch was renamed the Sludge Risk Assessment Branch (SRAB). The SRAB developed the final Part 503 regulation.

1.2 DESCRIPTION OF PART 503

The Part 503 standard consists of five subparts. Subpart A contains general provisions that apply to each of the three sewage sludge use or disposal practices. Subparts B and C pertain to specific requirements for land application and surface disposal of sewage sludge, respectively, while Subpart D, Pathogens and Vector Attraction, specifies requirements to control pathogens and other organisms, such as rodents, flies, and mosquitoes, that are capable of transporting infectious agents. Subpart E contains the provisions for sewage sludge incineration.

This section (Section One) provides an overview of Subpart A, General Provisions, and Subpart C, Surface Disposal, as well as a brief introduction to the applicable requirements in Subpart D. The text of all three subparts appears in full as Appendix A. Although much of the General Provisions section is relevant to all the regulated use or disposal practices, it also contains references that are specific to each practice. This discussion will focus on the general and specific requirements affecting the surface disposal of sewage sludge. Where there is overlap between the requirements of Subparts A and C, the information will be presented in the General Provisions section.

1.2.1 General Provisions

Subpart A of Part 503, General Provisions, consists of nine parts: the purpose and applicability of the regulation; the compliance period; permits and direct enforceability; the relationship to other regulations; additional or more stringent requirements; exclusions; the requirement for a person who prepares sewage sludge; sampling and analysis; and general definitions.

1.2.1.1 Purpose and Applicability

Part 503 establishes standards for the final use or disposal of sewage sludge generated during the treatment of domestic sewage in a treatment works. For sewage sludge placed on a

sewage sludge unit, the standard contains general requirements, pollutant limits, and management practices that protect public health from the reasonably anticipated adverse effects of pollutants in sewage sludge.¹ These elements of the standard are discussed in Subpart C, which includes pollutant limits for arsenic, chromium, and nickel. Subpart C also includes operational standards for pathogens and vector attraction reduction, and requirements for frequency of monitoring and recordkeeping. In addition, Subpart C includes reporting requirements for Class I sludge management facilities, treatment works with flow rates equal to or greater than 1 million gallons per day, and treatment works that serve a population of 10,000 people or greater that practice surface disposal of sewage sludge.

Subpart C applies to a *person* who prepares sewage sludge for placement on a surface disposal site; to *owners/operators* of a surface disposal site; to the *surface disposal site*; and to *sewage sludge* placed on a surface disposal site.

Subpart C does not apply to either sewage sludge being stored or treated or to land on which sewage sludge is placed for storage or treatment. It also does not apply to sewage sludge that remains on the land for longer than two years when the person who prepares the sewage sludge demonstrates that the land on which the sewage sludge remains is not an active sewage sludge unit. (See the rule in Appendix A (Part 503.20) for information needed for the demonstration.)

1.2.1.2 Compliance Period

Compliance with the Part 503 standard for the surface disposal of sewage sludge is to be achieved as expeditiously as practicable, but in no case later than one year from the date of publication in the *Federal Register*. If compliance with the standards requires construction of new pollution control facilities, compliance is to be achieved by two years from the date of publication in the *Federal Register*, or sooner if practicable.

¹One or more sewage sludge units constitute a surface disposal site.

Compliance with the frequency of monitoring, recordkeeping, and reporting requirements for all pollutants regulated under Subpart C is to begin 120 days after the effective date of the regulation.

1.2.1.3 Permits and Direct Enforceability

A permit is not a prerequisite for enforcement actions to be taken against any person who violates applicable Part 503 standards. However, the Part 503 standards for the surface disposal of sewage sludge and the requirements pertaining to frequency of monitoring, recordkeeping, and reporting may be put into effect through a permit under the following two conditions:

- A permit issued to a "treatment works treating domestic sewage" (TWTDS), as defined in 40 CFR Section 122.2 and in accordance with 40 CFR Parts 122 and 124, either by EPA or by a state that has a state sludge management program approved by EPA in accordance with 40 CFR Part 123 or 40 CFR Part 501.
- A permit issued under Subtitle C of the Solid Waste Disposal Act; Part C of the Safe Drinking Water Act; the Marine Protection, Research, and Sanctuaries Act of 1972; or the Clean Air Act.

A TWTDS is required to submit a permit application in accordance with either 40 CFR Section 122.21 or an approved state program. The standards and requirements in Subpart C are enforceable directly against any person who places sewage sludge on a surface disposal site.

1.2.1.4 Relationship to Other Regulations

Disposal of sewage sludge in a municipal solid waste landfill unit (as defined in 40 CFR 258.2) that complies with the requirements in 40 CFR Part 258 constitutes compliance with Section 405(d) of the CWA. Any person who prepares sewage sludge that is disposed in a municipal solid waste landfill unit must ensure that the sewage sludge meets the requirements in 40 CFR Part 258 concerning the quality of materials disposed.

1.2.1.5 Additional or More Stringent Requirements

On a case-by-case basis, the permitting authority (either EPA or a state with an EPA-approved sludge management program) may impose more stringent or additional requirements for the use or disposal of sewage sludge if necessary to protect public health and the environment from adverse effects of pollutants in sewage sludge. A state, a political subdivision, or an interstate agency also can impose requirements for the use or disposal of sewage sludge that either are more stringent than, or are in addition to, the requirements of Part 503.

1.2.1.6 Exclusions

Eight exclusions to the Part 503 rule apply to all three use or disposal practices:

- Treatment processes—processes used to treat domestic sewage or processes used to treat sewage sludge prior to final use or disposal, except as provided in 503.32 and 503.33, are not covered by Part 503.
- Selection of a use or disposal practice—The manner in which sewage sludge is used or disposed is a local determination and is not specified by Part 503.
- Sludge generated at an industrial facility—sludge generated in industrial wastewater treatment works that treat either industrial wastewater or industrial wastewater combined with domestic sewage generated at the industrial facility is not covered by Part 503. This exemption does not apply to sewage sludge treated separately from industrial waste at an industrial facility.
- Hazardous sewage sludge—sewage sludge determined to be hazardous in accordance with 40 CFR Part 261 is not covered by Part 503.
- Sewage sludge with high PCB concentration—sewage sludge that has a concentration of polychlorinated biphenyls (PCBs) equal to or greater than 50 milligrams per kilogram of total solids (dry weight basis) is not covered by Part 503.
- Grit and screenings—grit (e.g., sand, gravel, cinders, or other materials with a high specific gravity) or screenings (e.g., relatively large materials such as rags) generated during preliminary treatment of domestic sewage in a treatment works are not covered by Part 503.
- Drinking water treatment sludge—sludge generated during the treatment of either surface water or ground water used for drinking water is not covered by Part 503.

- Commercial and industrial septage—commercial septage or industrial septage, even if mixed with domestic septage, is not covered by Part 503.

1.2.1.7 Requirement for a Person Who Prepares Sewage Sludge

A person who prepares sewage sludge that is either fired in a sewage sludge incinerator, applied to the land, or placed on a surface disposal site must meet the applicable requirements of the Part 503 rule.

1.2.1.8 Sampling and Analysis

Representative samples of sewage sludge placed on an active sewage sludge unit must be collected and analyzed. Samples of sewage sludge (other than domestic septage) are to be analyzed for the regulated inorganic pollutants and pathogens according to methods specified in the Part 503 rule (see Appendix A, Part 503.8).

1.2.1.9 General and Special Definitions

The following words, phrases, acronyms, and concepts apply to information provided in this technical support document for the surface disposal of sewage sludge and are defined in Appendix A. These terms can be found either under the General Provisions subpart (Subpart A, 503.9) or the Surface Disposal subpart (Subpart C, 503.20).

General Definitions (503.9)

Base flood
Class I sludge management facility
CWA
Domestic septage
Domestic sewage
Dry weight basis
EPA
Feed crops
Fiber crops
Food crops

Special Definitions (503.20)

Active sewage sludge unit
Aquifer
Contaminate an aquifer
Cover
Displacement
Fault
Final cover
Holocene time
Leachate collection system
Liner

General Definitions (503.9) (cont.)

Ground water
Industrial wastewater
Municipality
Permitting authority
Person who prepares sewage sludge
Place sewage sludge
Pollutant
Pollutant limit
Runoff
Sewage sludge
State
Storage of sewage sludge
Treatment of sewage sludge
Treatment works
Wetland

Special Definitions (503.20) (cont.)

Lower explosive limit for methane gas
Qualified ground water scientist
Seismic impact zone
Sewage sludge unit
Sewage sludge unit boundary
Surface disposal site
Unstable area

1.2.2 Subpart C—Part 503 Standard and Other Requirements

For each sewage sludge use or disposal practice, a person to whom the rule applies must comply with general requirements, pollutant limits, management practices, and operational standard(s), as well as other requirements related to frequency of monitoring, recordkeeping, and reporting. The overview presented below discusses Subpart C which, in addition to Subpart A, regulates the surface disposal of sewage sludge. Section 1.3 below outlines the sections of this Technical Support Document where more detailed discussion of the Subpart C standard takes place.

1.2.2.1 General Requirements

The general requirements of the Part 503 regulation state that no person is permitted to place sewage sludge on an active sewage sludge unit unless the requirements of Subpart C are met. In addition, the general requirements include notification and closure requirements, as follows:

- Notification to the subsequent owner—The owner of a surface disposal site must provide the subsequent owner with written notification that sewage sludge was placed on the land.
- Closure—If an active sewage sludge unit is located within 60 meters of a fault, in an unstable area, or in a wetland, the unit must close by one year after the effective date of the regulation unless, in the case of a unit near a fault, the permitting authority specifies otherwise, or if the unit is in a wetland and the permit was issued under the Clean Water Act.

In addition, the owner/operator of an active sewage sludge unit must submit a written closure and post-closure plan to the permitting authority 180 days prior to closure explaining how the unit will be closed (e.g., how the leachate collection system will be operated and maintained for three years; a description of the system used to monitor methane gas; how public access will be restricted for three years).

1.2.2.2 Pollutant Limits

Subpart C of Part 503 establishes limits for three inorganic pollutants—arsenic, chromium, and nickel—for active sewage sludge units that do not contain a liner and leachate collection system. The pollutant limits do not apply to sewage sludge units with a liner and leachate collection system. In addition, these limits do not apply to domestic septage.

Stricter pollutant limits are set for active sewage sludge units whose boundaries are less than 150 meters from the property line. Alternatively, site-specific pollutant limits may be developed if requested by the owner/operator of a surface disposal site at the time of permit application. Site-specific pollutant limits can be used if the existing values for site parameters specified by the permitting authority are different from the values for those parameters used to develop the pollutant limits in Table 1 of Part 503.23 (see Appendix A) and if the permitting authority determines that site-specific pollutant limits are appropriate for the unit.

If site-specific pollutant limits are used, the concentration of each of the three inorganic pollutants covered in Subpart C may not exceed either: (a) the concentration of the pollutant determined during a site-specific assessment, or (b) the existing concentration of the pollutant in the sewage sludge, whichever is lower.

1.2.2.3 Operational Standard

Subpart C also includes operational standards to control pathogens and vectors (e.g., insects, rodents, birds) that are capable of transporting infectious agents. These requirements for pathogens and vector attraction reduction are detailed in Subpart D of the Part 503 rule. The pathogen requirements in Subpart D apply to sewage sludge (*excluding* domestic septage) placed on an active sewage sludge unit unless a specific soil cover requirement is met (503.33[b][11]). For domestic septage, pathogens are controlled through management practices as specified in Subpart C of Part 503 and 40 CFR Part 257 (see Section 8.1). The vector attraction reduction requirements apply to sewage sludge (*including* domestic septage) that is placed on an active sewage sludge unit.

1.2.2.4 Management Practices

Subpart C includes several management practices that are required for the surface disposal of sewage sludge, including:

- Threatened or endangered species—Sewage sludge cannot be placed on an active sewage sludge unit if it is likely to adversely affect a threatened or endangered species listed under Section 4 of the Endangered Species Act or its designated critical habitat. EPA will develop guidance to carry out this provision, consistent with the Endangered Species Act.
- Base flood—An active sewage sludge unit may not restrict the flow of a base flood.
- Geological stability—Three management practices state that an active sewage sludge unit must: (a) be located at least 60 meters from a fault (unless otherwise specified by the permitting authority); (b) not be located in an unstable area; and (c) if located in a seismic impact zone, withstand certain ground movements.
- Wetlands—An active sewage sludge unit may not be located in a wetland (unless a permit was issued under Section 402 or 404 of the Clean Water Act).
- Runoff—Two management practices specify that: (a) runoff from an active sewage sludge unit must be collected and disposed according to requirements of the National Pollutant Discharge Elimination System and any other applicable

requirements; and (b) the runoff collection system must have the capacity to handle runoff from a 24-hour, 25-year storm event.

- Leachate—Two management practices require that for active sewage sludge units with a liner and leachate collection system: (a) the leachate collection system must be operated and maintained; and (b) leachate must be collected and disposed according to applicable requirements. Both of these management practices must be conducted while the unit is active and for three years after the unit closes.
- Methane gas concentrations—For an active sewage sludge unit that receives a cover material, limits are established on the concentration of methane gas (based on its lower explosive limit) both within structures (i.e., buildings) on the surface disposal site and in air at the property line of the site. For a unit that receives a final cover at closure, the same concentration limits apply for three years after the unit closes, unless the permitting authority specifies otherwise.
- Crops—Food, feed, or fiber crops may not be grown on an active sewage sludge unit unless the owner/operator of the site demonstrates to the permitting authority that, through management practices, public health and the environment can be protected from reasonably anticipated adverse effects of pollutants in sewage sludge when the crops are grown.
- Grazing—Animals may not graze on an active sewage sludge unit unless the owner/operator of the site demonstrates to the permitting authority that public health and the environment can be protected from reasonably anticipated adverse effects of pollutants in sewage sludge when the animals are grazed.
- Public access—Public access to a surface disposal site must be restricted while the site contains an active sewage sludge unit and for three years after the last active sewage sludge unit closes.
- Ground water—Sewage sludge placed on an active sewage sludge unit may not contaminate an aquifer. This demonstration must be confirmed by the results of a ground water monitoring program developed by a qualified ground water scientist or a certification by a qualified ground water scientist.

1.2.2.5 Other Requirements (Frequency of Monitoring, Recordkeeping, and Reporting)

For sewage sludge placed on an active sewage sludge unit, there are additional requirements related to the Part 503 standard, including frequency of monitoring, recordkeeping, and reporting. The frequency of monitoring for arsenic, chromium, nickel, pathogens, and selected vector attraction reduction requirements ranges from once per year to once per month, depending on the amount of sewage sludge placed on an active sewage sludge unit. The

regulation allows the permitting authority to modify the frequency of monitoring for the three pollutants and for pathogens after the sewage sludge has been monitored for a period of two years in accordance with Subpart C, as long as the frequency of monitoring is at least once per year. In addition, continuous monitoring for methane gas is required within structures on the surface disposal site and in air at the property line while the site contains an active sewage sludge unit that is covered, and for three years after the unit closes if a final cover is placed on the sewage sludge. If the vector attraction reduction requirements are met for domestic septage placed on an active sewage sludge unit, each container of domestic septage must be monitored for compliance with those requirements.

Any person who prepares sewage sludge for placement on an active sewage sludge unit must retain certain data for a period of five years. These data include the concentrations of arsenic, chromium, and nickel in the sewage sludge, as well as certification that the requirements for pathogens and vector attraction reduction (if achieved through a preparation process) have been met, along with a description of how these requirements have been met. In addition, the owner/operator of a surface disposal site must retain pollutant concentration data and must identify and describe how required management practices have been met. Additionally, the owner/operator must certify and describe vector attraction reduction requirements achieved through a management-type practice (e.g., daily cover). Persons placing domestic septage on a surface disposal site must retain information certifying that vector attraction reduction requirements have been met, along with a description of how these requirements have been met.

The reporting requirements under Subpart C pertain to Class I sludge management facilities and treatment works with a flow rate equal to or greater than one million gallons per day (MGD) or that serve a population of 10,000 people or greater. These specified facilities where sewage sludge is placed on a surface disposal site are required to report yearly to the permitting authority.

1.3 SCOPE OF THE TECHNICAL SUPPORT DOCUMENT FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE

This document consists of 10 sections, including this introduction. The next section, Section Two, provides an overview of the different types of surface disposal sites, such as monofills and surface impoundments. Section Three is a general discussion of EPA risk assessment methodology, while Section Four discusses the process by which EPA selected the pollutants for which the risk assessment was conducted.

Section Five provides a detailed discussion of the risk assessment methodology established for the surface disposal of sewage sludge, which is the basis for developing pollutant limits on the concentration of the three inorganic pollutants in sewage sludge. This section also contains sample calculations deriving the pollutant criteria used to develop the pollutant limits. In addition, it explains the rationale for using the numerous technical and risk-based factors in the risk assessment equations. Section Six presents the pollutant limits for the surface disposal of sewage sludge and explains their derivation from the risk assessment results. Section Seven provides more detail on the management practices required under Subpart C, while Section Eight presents the operational standards for pathogens and vector attraction reduction. Section Nine describes the frequency of monitoring, recordkeeping, and reporting requirements. References appear in Section Ten, and six appendices are provided as supporting material.

Appendix A consists of the text of Part 503, Subpart A, Subpart C, and Subpart D. Appendix B, Appendix C, and Appendix D all pertain to aspects of the detailed risk assessment presented in Section Five. Appendix B relates to the partitioning of the evaluated contaminants among air, water, and solids in the soil. Appendix C presents the derivation of the first-order coefficient for losses from leaching. Appendix D derives a "square wave" function for the monofill prototype. In Appendix E, a detailed explanation is given for the deletion of pollutants from the Part 503 regulation based on the results of the risk assessment. Appendix F provides the calculation of the amount of sewage sludge used or disposed, which is used to determine the Part 503 frequency of monitoring requirements.

SECTION TWO

SURFACE DISPOSAL OF SEWAGE SLUDGE

2.1 INTRODUCTION

Surface disposal is defined in the Part 503 regulation as an area of land that contains one or more active sewage sludge units. A sewage sludge unit is an area of land on which only sewage sludge is placed for final disposal. Various types of surface disposal sites exist, including monofills (landfills containing only sewage sludge), surface impoundments, lagoons, waste piles, and dedicated sites. The Part 503 regulation does not require sewage sludge units to have a daily or final cover, as is required of some other types of solid waste disposal practices (e.g., municipal landfills). However, cover material, usually soil, is sometimes used at surface disposal sites to minimize odors and help prevent vectors (e.g., insects, rodents, birds) from contacting the sewage sludge and spreading contaminants. Some of the different types of surface disposal sites regulated by the Part 503 rule are discussed in more detail later in this section.

2.2 EXCLUSIONS

The Part 503 regulation applies only to surface disposal sites used for final disposal of sewage sludge and not to sites on which sewage sludge is treated or on which sewage sludge is stored for less than 2 years. Treatment is the preparation of sewage sludge for final use or disposal. Examples of treatment processes include thickening, stabilizing, and dewatering. Storage is the placement of sewage sludge on an area of land (except for treatment) on which the sewage sludge remains for 2 years or less. Therefore, sites such as aeration lagoons that are used for treatment of sewage sludge are not regulated by the Part 503 rules, and sites such as storage piles are not covered for 2 years, unless the treatment works can justify a longer storage period. The Part 503 regulation also does not apply to sites where sewage sludge is codisposed with refuse (e.g., municipal solid waste landfills).

2.3 TYPES OF SURFACE DISPOSAL SITES

2.3.1 Monofills

Monofills are landfills that contain only dewatered sewage sludge. Types of monofills include trenches and area-fills (mounds, layers, and diked containments). Monofill trenches can be wide or narrow, with each size requiring different sewage sludge characteristics. Trenches range from 1 to 15 meters (m) (3-50 feet [ft]) wide. In narrow trenches (1-3 m [3-10 ft] wide), dewatered sewage sludge is usually deposited in the trench from a haul vehicle alongside the ditch. To ensure that the sewage sludge will spread evenly throughout a narrow trench, sewage sludge should be less than 30 percent solids and the trench floor should be nearly level.

A wide trench (3-15 m [10-50 ft] wide) allows a vehicle to work within the trench itself. For wide monofill trenches, the sewage sludge should be at least 30 percent solids (which may include bulking material, such as fine sand) to ensure that it will stay in piles and not slump. The addition of a bulking agent is generally not cost-effective if the sewage sludge solids content is less than about 20 percent. If the sewage sludge solids content is too low, the sewage sludge should undergo additional dewatering at the treatment plant before being transported to the monofill.

Sewage sludge in monofill trenches is often covered with soil the same day it is deposited to minimize odors and to prevent insects, birds, and other vectors from contacting the sewage sludge and spreading contaminants. As each new trench is dug, the excavated soil is used to cover the sewage sludge in a nearby trench. If the sewage sludge is solid enough to support a vehicle (greater than about 30 percent solids), a soil cover can be applied by a vehicle within the trench. For sewage sludge containing less than 30 percent solids, the cover should be applied by a front-end loader or dragline next to the ditch.

Sewage sludge applications for narrow trenches range from about 460 to 2,120 dry metric tons per hectare (dry mt/ha) (200 to 940 tons per acre [tons/ac]), including areas between trenches. Wide trench operations can accommodate larger sewage sludge applications than narrow trenches, ranging from about 1,200 to 5,430 dry mt/ha (530-2,440 tons/ac).

If covers are used for monofill trenches, the sewage sludge generally should contain at least 20 percent solids to support the cover material. Narrow trenches can handle sewage sludge with as low as 15 percent solids because the ground on either side helps support the cover.

At area fills, another type of monofill, sewage sludge is placed on the original ground surface. Excavation is not required (as it is with trenches) because sewage sludge is not placed below the ground surface. Area fills are often used at sites with shallow depths to bedrock or ground water. There are three types of area-fill applications: area-fill mounds, area-fill layers, and diked containment. These are discussed below.

In area-fill mounds, the sewage sludge solids content should be no more than 20 percent. Sewage sludge is mixed with a soil-bulking agent to produce a mixture that is physically more stable and has greater weight-bearing capacity. The sewage sludge is usually mixed at one location and then hauled to the filling area. At the filling area, the mixture is stacked into mounds approximately 2 m (6 ft) high, and 1 m (3 ft) of cover material is applied.

In area-fill layer applications, sewage sludge is received at the site and mixed with a soil-bulking agent. The mixture is spread evenly in layers from 0.2 to 1 m (0.5 to 3 ft) thick in a number of applications. An interim soil cover is applied between consecutive layers in 0.2 to 0.3 m (0.5 to 1 ft) thick applications. The final soil cover is from 0.6 to 1 m (2 to 3 ft) thick.

In diked containment applications, dikes are constructed on level ground around all four sides of a containment area. Access is provided to the top of the dike so that haul vehicles can dump sewage sludge directly into the containment area. Usually, diked containment operations are conducted without adding soil-bulking agents. Diked containments are relatively large, with typical dimensions of 3 to 152 m (10 to 500 ft) wide, 30 to 61 m (100 to 200 ft) long, and 0.3 to 9 m (1 to 30 ft) deep.

2.3.2 Surface Impoundments

Surface impoundments are surface disposal sites for sewage sludge generally containing more liquid than sewage sludge placed in monofills. The solids content of sewage sludge in surface impoundments is usually between 2 and 5 percent. The water level in the impoundment is maintained at a constant height by using an outflow pipe. Liquid usually leaves the impoundment through both the outflow pipe and seepage through the base of the impoundment. Settling of particulate matter occurs over time, and a layer of sediment accumulates on the floor of the impoundment. Eventually, the sediment layer reaches the top of the impoundment and no further inflow is possible. The impoundment is then either covered and closed or the sewage sludge can be dredged and disposed in another manner.

2.3.3 Dedicated Sites

Dedicated sites are surface disposal sites on which sewage sludge is spread at greater than agronomic rates. Thus, the sites do not qualify as land application sites under Subpart B of Part 503.² These sites are often located onsite at the treatment works and receive multiple applications of sewage sludge each year for a number of years, usually for the sole purpose of final disposal. Dedicated sites range in size from less than 10 acres to greater than 10,000 acres. Public access to dedicated sites is strictly controlled to protect public health.

Very few dedicated sites are used to grow food, feed, and/or fiber crops or vegetative cover. These are known as dedicated beneficial use sites. The sewage sludge increases the soil's productivity and can reduce soil erosion and acidity. The high application rates of sewage sludge placed on these sites can reclaim and restore marginal and disturbed soils, such as strip mines, by supplying nutrients that act as fertilizers, as well as organic matter that conditions the soil.

²An agronomic rate is the whole sludge application rate (dry weight basis) designed to: (1) provide the amount of nitrogen needed by the food crop, feed crop, fiber crop, cover crop, or vegetation grown on the land and (2) minimize the amount of nitrogen in the sewage sludge that passes below the root zone of the crop or vegetation grown on the land to the ground water.

SECTION THREE

RISK ASSESSMENT METHODOLOGY

This chapter discusses current EPA methods and established Agency policy for performing a risk assessment. This process was outlined originally by the National Academy of Sciences (NAS, 1983) and was established as final Risk Assessment Guidelines in the Federal Register (U.S. EPA, 1986b). Five types of guidelines were issued:

- Guidelines for Carcinogen Assessment
- Guidelines for Estimating Exposure
- Guidelines for Mutagenicity Risk Assessment
- Guidelines for Health Effects of Suspect Developmental Toxicants
- Guidelines for Health Risk Assessment of Chemical Mixtures.

The Risk Assessment Methodology consists of four distinct steps: hazard identification, dose-response evaluation, exposure evaluation, and characterization of risks.

3.1 HAZARD IDENTIFICATION

The primary purposes of hazard identification are to determine whether the chemical poses a hazard and whether there is sufficient information to perform a quantitative risk assessment. Hazard identification consists of gathering and evaluating all relevant data that help determine whether a chemical poses a specific hazard, then qualitatively evaluating those data on the basis of the type of health effect produced, the conditions of exposure, and the metabolic processes that govern chemical behavior within the body. Thus, the goals of hazard identification are to determine whether it is appropriate scientifically to infer that effects observed under one set of conditions (e.g., in experimental animals) are likely to occur in other settings (e.g., in human beings), and whether data are adequate to support a quantitative risk assessment.

The first step in hazard identification is gathering information on the toxic properties of chemical substances. The principal methods are animal studies and controlled epidemiological investigations of exposed human populations.

The use of animal toxicity studies is based on the longstanding assumption that effects in human beings can be inferred from effects in animals. There are three categories of animal bioassays: acute exposure tests, subchronic tests, and chronic tests. The usual starting point for such investigations is the study of acute toxicity in experimental animals. Acute exposure tests expose animals to high doses for short periods of time, usually 24 hours or less. The most common measure of acute toxicity is the lethal dose (LD_{50}), the average dose level that is lethal to 50 percent of the test animals. LD_{50} refers to oral doses. LC_{50} designates the inhalation dose at which 50 percent of the animals exposed died. LC_{50} is also used for aquatic toxicity tests and refers to the concentration of the test substance in the water that results in 50 percent mortality in the test species. Substances exhibiting a low LD_{50} (e.g., for sodium cyanide, 6.4 mg/kg) are more acutely toxic than those with higher values (e.g., for sodium chloride, 3,000 mg/kg) (NIOSH, 1979).

Subchronic tests for chemicals involve repeated exposures of test animals for 5 to 90 days, depending on the animal, by exposure routes corresponding to human exposures. These tests are used to determine the No Observed Adverse Effect Level (NOAEL), the Lowest Observed Adverse Effect Level (LOAEL), and the Maximum Tolerated Dose (MTD). The MTD is the largest dose a test animal can receive for most of its lifetime without demonstrating adverse effects other than cancer. In studies of chronic effects of chemicals, test animals receive daily doses of the test agent for approximately 2 to 3 years. The doses are lower than those used in acute and subchronic studies, and the number of animals is larger because these tests are trying to detect effects that will be observed in only a small percentage of animals.

The second method of evaluating health effects uses epidemiology—the study of patterns of disease in human populations and the factors that influence these patterns. In general, scientists view well-conducted epidemiological studies as the most valuable information from which to draw inferences about human health risks. Unlike the other approaches used to evaluate health effects, epidemiological methods evaluate the direct effects of hazardous substances on human beings. These studies also help identify human health hazards without

requiring prior knowledge of disease causation, and they complement the information gained from animal studies.

Epidemiological studies compare the health status of a group of persons who have been exposed to a suspected causal agent with that of a comparable nonexposed group. Most epidemiological studies are either case-control studies or cohort studies. In case-control studies, a group of individuals with specific disease is identified (cases) and compared with individuals not having the disease (controls) in an attempt to ascertain commonalities in exposures they may have experienced in the past. Cohort studies start with a group of people (a cohort) considered free of the disease under investigation. The health status of the cohort known to have a common exposure is examined over time to determine whether any specific condition or cause of death occurs more frequently than might be expected from other causes.

Epidemiological studies are well suited to situations in which exposure to the risk agent is relatively high; the adverse health effects are unusual (e.g., rare forms of cancer); the symptoms of exposure are known; the exposed population is clearly defined; the link between the causal risk agent and adverse effects in the affected population is direct and clear; the risk agent is present in the bodies of the affected population; and high levels of the risk agent are present in the environment.

The next step in hazard identification is to combine the pertinent data to ascertain the degree of hazard associated with each chemical. In general, EPA uses different approaches for qualitatively assessing the risk or hazard associated with carcinogenic versus noncarcinogenic effects. For noncarcinogenic health effects (e.g., systemic toxicity), the Agency's hazard identification/weight-of-evidence determination has not been formalized and is based only on a qualitative assessment.

EPA's guidelines for carcinogenic risk assessment (U.S. EPA, 1986b) group all human and animal data reviewed into the following categories based on degree of evidence of carcinogenicity:

- Sufficient evidence
- Limited evidence (e.g., in animals, an increased incidence of benign tumors only)

- Inadequate evidence
- No data available
- No evidence of carcinogenicity.

Human and animal evidence of carcinogenicity in these categories is combined into the following weight-of-evidence classification scheme:

- Group A—Human carcinogen
- Group B—Probable human carcinogen
 - B1—Higher degree of evidence
 - B2—Lower degree of evidence
- Group C—Possible human carcinogen
- Group D—Not classifiable as to human carcinogenicity
- Group E—Evidence of noncarcinogenicity

Group B, probable human carcinogens, is usually divided into two subgroups: B1, chemicals for which there is some limited evidence of carcinogenicity from epidemiology studies; and B2, chemicals for which there is sufficient evidence from animal studies but inadequate evidence from epidemiology studies. EPA treats chemicals classified in categories A and B as suitable for quantitative risk assessment. Chemicals classified as Category C receive varying treatment with respect to dose-response assessment, and they are determined on a case-by-case basis. Chemicals in Groups D and E do not have sufficient evidence to support a quantitative dose-response assessment.

The following factors are evaluated by judging the relevance of the data for a particular chemical:

- Quality of data.
- Resolving power of the studies (significance of the studies as a function of the number of animals or subjects).
- Relevance of route and timing of exposure.
- Appropriateness of dose selection.

- Replication of effects.
- Number of species examined.
- Availability of human epidemiologic study data.
- Relevance of tumors observed (e.g., forestomach, mouse liver, male rat kidney)

Although the information gathered during the course of identifying each chemical hazard is not used to estimate risk quantitatively, hazard identification enables researchers to characterize the body of scientific data in such a way that two questions can be answered: (1) Is a chemical a hazard? and (2) Is a quantitative assessment appropriate? The following two sections discuss how such quantitative assessments are conducted.

3.2 DOSE-RESPONSE EVALUATION

Estimating the dose-response relationships for the chemical under review is the second step in the risk assessment methodology. Evaluating dose-response data involves quantitatively characterizing the connection between exposure to a chemical (measured in terms of quantity and duration) and the extent of toxic injury or disease. Most dose-response relationships are estimated based on results of animal studies, because even good epidemiological studies rarely have reliable information on exposure. Therefore, this discussion focuses primarily on dose-response evaluations based on animal data.

There are two general approaches to dose-response evaluation, depending on whether the health effects are based on threshold or nonthreshold characteristics of the chemical. In this context, **thresholds** refer to exposure levels below which no adverse health effects are assumed to occur. For effects that involve altering genetic material (including carcinogenicity and mutagenicity), the Agency's position is that effects may take place at very low doses, and therefore, they are modeled with no thresholds. For most other biological effects, it is usually (but not always) assumed that "threshold" levels exist.

For nonthreshold effects, the key assumption is that the dose-response curve for such chemicals exhibiting these effects in the human population achieves zero risk only at zero dose. A mathematical model is used to extrapolate response data from doses in the observed

(experimental) range to response estimates in the low-dose ranges. Scientists have developed several mathematical models to estimate low-dose risks from high-dose experimental risks. Each model is based on general theories of carcinogenesis rather than on data for specific chemicals. The choice of extrapolation model can have a significant impact on the dose-response estimate. For this reason, the Agency's cancer assessment guidelines recommend the use of the multistage model, which yields estimates of risk that are conservative, representing a plausible upper limit of risk. With this approach, the estimate of risk is not likely to be lower than the true risk (U.S. EPA, 1986b).

The potency value, referred to by the Carcinogenic Assessment Group as q_1^* , is the quantitative expression derived from the linearized multistage model that gives a plausible upper-bound estimate to the slope of the dose-response curve in the low-dose range. The q_1^* is expressed in terms of risk-per-dose, and has units of $(\text{mg/kg}\cdot\text{day})^{-1}$. These values should be used only in dose ranges for which the statistical dose-response extrapolation is appropriate. EPA's q_1^* values can be found in the Integrated Risk Information System (IRIS), accessible through the National Library of Medicine.

Dose-response relationships are assumed to exhibit threshold effects for systemic toxicants or other compounds exhibiting noncarcinogenic, nonmutagenic health effects. Dose-response evaluations for substances exhibiting threshold responses involve calculating what is known as the Reference Dose (oral exposure) or Reference Concentration (inhalation exposure), abbreviated to RfD and RfC, respectively. This measure is used as a threshold level for critical noncancer effects below which a significant risk of adverse effects is not expected. The RfDs and RfCs developed by EPA can be found in IRIS.

The RfD/RfC methodology uses four experimental levels: No Observed Effect Level (NOEL), No Observed Adverse Effect Level (NOAEL), Lowest Observed Effect Level (LOEL), or Lowest Observed Adverse Effect Level (LOAEL). Each level is stated in $\text{mg/kg}\cdot\text{day}$, and all the levels are derived from laboratory animal and/or human epidemiology data. When the appropriate level is determined, it is then divided by an appropriate uncertainty (safety) factor. The magnitude of safety factors varies according to the nature and quality of the data from which the NOAEL or LOAEL is derived. The safety factors, ranging from 1 to 10,000, are used to extrapolate from acute to chronic effects, interspecies sensitivity, and variation in sensitivity in human populations. They are also used to extrapolate from a LOAEL to a NOAEL. Ideally, for

all threshold effects, a set of route-specific and effect-specific thresholds should be developed. If information is available for only one route of exposure, this value is used in a route-to-route extrapolation to estimate the appropriate threshold. Once these values are derived, the next step is to estimate actual human (or animal) exposure.

3.3 EXPOSURE EVALUATION

Exposure evaluation uses data concerning the nature and size of the population exposed to a substance, the route of exposure (i.e., oral, inhalation, dermal), the extent of exposure (concentration times time), and the circumstances of exposure.

There are two ways of estimating environmental concentrations:

- Directly measuring levels of chemicals (monitoring)
- Using mathematical models to predict concentrations (modeling)

In addition, an analysis of population exposure is necessary.

3.3.1 Monitoring

Monitoring involves collecting and analyzing environmental samples. These data provide the most accurate information about exposure. The two kinds of exposure monitoring are personal monitoring and ambient (or site and location) monitoring.

Most exposure assessments are complicated by the fact that human beings move from place to place and are therefore exposed to different risk agents throughout the day. Some exposure assessments attempt to compensate for this variability by personal monitoring. Personal monitoring uses one or more techniques to measure the actual concentrations of hazardous substances to which individuals are exposed. One technique is sampling air and water. The amount of time spent in various microenvironments (i.e., home, car, or office), may be combined

with data on environmental concentrations of risk agents in those microenvironments to estimate exposure.

Personal monitoring may also include the sampling of human body fluids (e.g., blood, urine, or semen). This type of monitoring is often referred to as **biological monitoring** or **biomonitoring**. Biological markers (also called biomarkers) can be classified as markers of exposure, of effect, and of susceptibility. Biological markers of exposure measure exposure either to the exogenous material, its metabolite(s), or to the interaction of the xenobiotic agent with the target cell within an organism. An example of a biomarker of exposure is lead concentration in blood. In contrast, biologic markers of effect measure some biochemical, physiologic, or other alteration within the organism that points to impaired health. (Sometimes the term biomonitoring is also used to refer to the regular sampling of animals, plants, or microorganisms in an ecosystem to determine the presence and accumulation of pollutants, as well as their effects on ecosystem components.)

Ambient monitoring (or site or location monitoring) involves collecting samples from the air, water, soil, or sediments at fixed locations, then analyzing the samples to determine environmental concentrations of hazardous substances at the locations. Exposures can be further evaluated by modeling the fate and transport of the pollutants.

3.3.2 Modeling

Measurements are a direct and preferred source of information for exposure analysis. However, such measurements are expensive and are often limited geographically. The best use of such data is to calibrate mathematical models that can be more widely applied. Estimating concentrations using mathematical models must account not only for physical and chemical properties related to fate and transport, but must also document mathematical properties (e.g., analytical integration vs. statistical approach), spatial properties (e.g., one, two, or three dimensions), and time properties (steady-state vs. nonsteady-state).

Hundreds of models for fate, transport, and dispersion from the source are available for all media. Models can be divided into five general types by media: atmospheric models, surface-water models, ground-water and unsaturated-zone models, multimedia models, and food-chain

models. These five types of models are primarily applicable to chemicals or to radioactive materials associated with dusts and other particles.

Selecting a model for a given situation depends on the following criteria: capability of the model to account for important transport, transformation, and transfer mechanisms; fit of the model to site-specific and substance-specific parameters; data requirements of the model, compared to availability and reliability of off-site information; and the form and content of the model output that allow it to address important questions regarding human exposures.

To the extent possible, selection of the appropriate fate and transport model should follow guidelines specified for particular media where available; for example, the Guidelines on Air Quality Models (U.S. EPA, 1986c).

3.3.3 Population Analysis

Population analysis involves describing the size and characteristics (e.g., age/sex distribution), location (e.g., workplace), and habits (e.g., food consumption) of potentially exposed human and nonhuman populations. Census and other survey data often are useful in identifying and describing populations exposed to a chemical.

Integrated exposure analysis involves calculating exposure levels, along with describing the exposed populations. An integrated exposure analysis quantifies the contact of an exposed population to each chemical under investigation via all routes of exposure and all pathways from the sources to the exposed individuals. Finally, uncertainty should be described and quantified to the extent possible.

3.4 RISK CHARACTERIZATION

This final step in the risk assessment methodology involves integrating the information developed in hazard identification, dose-response assessment, and exposure assessment to derive quantitative estimates of risk. Qualitative information should also accompany the numerical risk estimates, including a discussion of uncertainties, limitations, and assumptions. It is useful to

distinguish methods used for chemicals exhibiting threshold effects (i.e., most noncarcinogens) from those believed to lack a response threshold (i.e., carcinogens).

For carcinogens, individual risks are generally represented as the probability that an individual will contract cancer in a lifetime as a result of exposure to a particular chemical or group of chemicals. Population risks are usually estimated based on expected or average exposure scenarios (unless information on distributions of exposure is available). The number of persons above a certain risk level, such as 10^{-6} , or above a series of risk levels (10^{-5} , 10^{-4} , etc.), is another useful descriptor of population risks. Thus, individual risks also may be presented using cumulative frequency distributions, where the total number of people exceeding a given risk level is plotted against the individual risk level.

For noncarcinogens, dose-response data above the threshold are usually lacking. Therefore, risks are characterized by comparing the dose or concentration to the threshold level, using a ratio in which the dose is placed in the numerator and the threshold in the denominator. Aggregate population risks for noncarcinogens can be characterized by the number of people exposed above the RfD or RfC. Recall that the hazard identification step for threshold chemicals is addressed qualitatively because no formal Agency weight-of-evidence evaluation is currently available for noncarcinogenic chemicals. The same approach can be used to assess both acute and chronic hazards. For assessing acute effects, the toxicity data and exposure assessment methods must account for the appropriate duration of exposure.

SECTION FOUR

POLLUTANTS AND PATHWAYS OF CONCERN FOR PART 503 RISK ASSESSMENT FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE

Which pollutants are regulated under the Part 503 regulation depends on the sewage sludge use or disposal practice—surface disposal, land application, or incineration. Subpart C, Surface Disposal, establishes limits for three pollutants for sewage sludge placed on a surface disposal site. This section describes how EPA selected the 17 pollutants for which the Agency conducted detailed risk assessments and discusses the data bases used to collect information about the pollutants. Following a detailed explanation of the risk assessment methodology in Section Five, Section Six explains how EPA used the risk assessment results to select the three pollutants and establish limits for these pollutants in the final Part 503 regulation for sewage sludge placed on a surface disposal site.

Since the pollutants to be regulated under all sewage sludge use or disposal practices were selected concurrently, this section discusses the selection process broadly and, where appropriate, focuses on the pollutants of concern in sewage sludge placed on a surface disposal site. Those interested in greater detail on the pollutant evaluation process are encouraged to refer to the following documents: *The Record of Proceedings on the OWRS Municipal Sewage Sludge Committees* and *Summary of the Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge* (U.S. EPA, 1983a; 1985a).

4.1 INITIAL LIST OF POLLUTANTS

In the Spring of 1984, EPA enlisted the assistance of federal, state, academic, and private sector experts to determine which pollutants likely to be found in sewage sludge should be further examined as possible candidates for regulation under the Part 503 standard. These experts screened a list of approximately 200 pollutants in sewage sludge that, when sewage sludge is used or disposed, could cause adverse human health or environmental effects. Many of the pollutants placed on the initial list for consideration came from the Clean Water Act's list of

Priority Pollutants and Appendix VIII of the Resource Conservation and Recovery Act, and were based on available information such as human health effects, domestic and wildlife effects, aquatic toxicity, plant uptake, phytotoxicity, and frequency of occurrence. The experts were requested to review and revise the list, adding or deleting pollutants, based on the following criteria:

- Pollutants in sewage sludge for which an adequate database existed to indicate the hazard posed to human health and/or the environment (i.e., potential health hazards);
- Pollutants in sewage sludge for which sufficient data existed to exclude them as hazards to human health and/or the environment; or
- Pollutants in sewage sludge for which insufficient data were available to determine if they posed a human health and/or environmental problem.

Based on qualitative assessments of each of the approximately 200 initial pollutants, the committee of experts recommended that the Agency gather additional environmental information on 50 pollutants (see Table 4-1) and 7 pathogens. The other 150 pollutants were not included on the list because the committee judged them not likely to cause adverse human health or environmental effects if disposed properly. EPA developed an environmental profile for each of the 50 pollutants and 7 pathogens selected for further evaluation. Each profile consisted of a compilation of data on toxicity, occurrence, and fate and effects of the pollutant, and a "hazard index" to rank the degree of hazard each of the 50 pollutants posed for the major exposure pathway(s) for each use or disposal practice (U.S. EPA, 1985a,b,c,d)

Environmental profiles, including hazard indices, were developed for pollutants likely to be found when sewage sludge is applied to land, incinerated, disposed in the ocean, or placed in a landfill (monofill). Ocean disposal of sewage sludge has since been prohibited. At the time the environmental profiles were developed, types of surface disposal practices other than placement in landfills/monofills were not included as part of the regulatory development effort because they were considered isolated practices that would not be expected to pose significant risks. Later in the development of the Part 503 regulation, however, the Agency concluded that the proposed rule should cover disposal of sewage sludge in other types of surface disposal sites, including surface impoundments, lagoons, waste piles, and dedicated sites. EPA determined that

the pollutants of concern for regulating all types of surface disposal sites were the same as those for landfilling (monofilling), since the most critical pathway of exposure for all types of surface disposal sites is through potential ground water contamination. In addition, the hazard indices developed for landfilling were based on worst-case assumptions and, therefore, would adequately identify pollutants of concern for other types of surface disposal sites.

Of the 50 pollutants selected for further consideration through development of environmental profiles and hazard indices, the OWRS expert committee identified 28 as potentially of concern for landfilling (see Table 4-1). Not every pollutant was considered a potential risk under each use or disposal practice because different use or disposal practices can result in different exposure levels for the same pollutant. A summary of the results of the environmental profiles and hazard indices for pollutants in landfilled sewage sludge is included in the *Summary of the Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge* (U.S. EPA, 1985a). Although cadmium and chromium initially were not identified in the hazard profile as posing a potential ground-water risk for landfilling, they were later added to the risk assessment analysis for consistency with calculations for land application.

4.2 ENVIRONMENTAL PROFILES AND HAZARD INDICES

During 1984 and 1985, the Agency collected data from published scientific papers on the list of 50 pollutants of concern, including information on toxicity and persistence; pathways by which the pollutants travel through the environment to a receptor organism (plant, animal, or human); mechanisms that transport or bind the pollutants; and the effects of the pollutants on the target organism. EPA also analyzed data on the relative frequencies and concentrations of sewage sludge pollutants as part of an Agency study of 45 POTWs in 40 cities. The study was officially called the "Fate of Priority Pollutants in Publicly Owned Treatment Works," but was better known as the "40-City Study" (U.S. EPA, 1982a). The 40-City Study contained data on the concentrations of 40 pollutants in sewage sludge (12 metals, 6 base neutral organic compounds, 6 volatile organic compounds, 9 pesticides, and 7 polychlorinated biphenyls [PCBs]).

TABLE 4-1

**POLLUTANTS SELECTED FOR
ENVIRONMENTAL PROFILES/HAZARD INDICES***

Pollutants	Land Application	Surface Disposal Site (formerly Landfill)	Incineration
Aldrin/Dieldrin	X		X
Arsenic	X	X	X
Benzene		X	X
Benzo(a)anthracene	X		X
Benzo(a)pyrene	X	X	X
Beryllium			X
Bis (2-ethylhexyl) phthalate	X	X	X
Cadmium	X	X	X
Carbon tetrachloride			X
Chlordane	X	X	X
Chlorinated dibenzodioxins			X
Chlorinated dibenzofurans			X
Chloroform			X
Chromium	X	X	X
Cobalt	X	X	
Copper	X	X	X
Cyanide		X	
DDT/DDD/DDE	X	X	X
2,4-Dichlorophenoxy-acetic acid		X	
Fluoride	X		
Heptachlor	X		X
Hexachlorobenzene	X		
Hexachlorobutadiene	X		
Iron	X		
Lead	X	X	X

TABLE 4-1 (continued)

Pollutants	Land Application	Surface Disposal Site (formerly Landfill)	Incineration
Lindane	X	X	X
Malathion		X	
Mercury	X	X	X
Methylene bis (2-chloroaniline)	X		
Methylene chloride	X	X	X
Methylethyl ketone		X	
Molybdenum	X	X	
Nickel	X	X	X*
n-Nitrosodimethylamine	X	X	
PCBs	X	X	X
Pentachlorophenol	X		
Phenanthrene		X	X
Phenol		X	
Selenium	X	X	X
Tetrachloroethylene			X
Toxaphene	X	X	X
Trichloroethylene	X	X	
Tricresol phosphate	X		
Vinyl chloride			X
Zinc	X	X	X

*Excludes pollutants selected for environmental profiles and hazard indices for the ocean disposal of sewage sludge.

For surface disposal of sewage sludge, drinking contaminated ground water initially was determined to be the only critical pathway. A second pathway, inhaling pollutants that volatilize from a surface disposal site, was not considered at this early stage because EPA assumed that good management practices were in place at sewage sludge landfills and that the volatilization of pollutants was not a likely route of exposure. The volatilization pathway, however, was considered in the later, more detailed risk assessment conducted for the final Part 503 regulation.

EPA used the data collected on the 50 pollutants to assess the likelihood of each pollutant affecting human health or the environment adversely. For this analysis, EPA relied on rudimentary risk assessments to predict at what concentration a pollutant would occur in surface or ground water, soil, air, or food. EPA then compared the predicted pollutant concentration with an Agency human health criterion to determine whether, at that concentration, the pollutant could be expected to have an adverse effect.

For carcinogens, if the calculated risk using the predicted concentration was lower than an allowable cancer risk level of 1×10^{-6} (1 person in 1,000,000),¹ the pollutant was not considered to have an adverse effect. For noncarcinogens, adverse impact hinged on whether the pollutant concentration exceeded an existing standard. To determine the human health impact of the pollutants of concern, EPA assumed worst-case conditions that would maximize the pollutant exposure.

The Agency used the rudimentary risk assessments to score and rank each pollutant according to its "hazard index," screening out those pollutants not expected to have an adverse human health impact before proceeding with more thorough, detailed modeling for pollutants considered to be of concern. Two hazard indices were developed for landfilling: (1) an index indicating effects of a pollutant on ground water; and (2) an index of human toxicity/cancer risk

¹In the initial phase of the pollutant selection process, EPA chose the 1×10^{-6} risk level as being protective of human health for a most sensitive individual exposed under a hypothetical worst-case scenario. Later EPA analyses for the proposed Part 503 rule used a 1×10^{-5} risk level for sewage sludge incineration and a 1×10^{-4} risk level for the other use or disposal practices, while the final rule uses a risk level of 1×10^{-4} for all use or disposal practices. The 1×10^{-6} risk level used at the outset of the pollution selection process allowed more pollutants to be evaluated than those later selected for further, more extensive analysis under a 1×10^{-4} risk level.

resulting from ground water contamination. The ground water contamination index was based on the EPA Exposure Assessment Group's model, "Rapid Assessment of Potential Ground Water Contamination Under Emergency Response Conditions" (U.S. EPA, 1983b). The ground water index estimated the pollutant transport through the soil to the water table beneath the landfill and through the aquifer to a nearby well. The human toxicity/cancer risk index for noncarcinogens was determined by comparing the estimated exposure from drinking ground water beneath a sewage sludge landfill with available acceptable daily intake values for the pollutants of concern. For carcinogens, the human/toxicity cancer risk index was based on comparing estimated exposure to a particular pollutant of concern from drinking from a well supplied by ground water beneath a landfill to the intake level of that pollutant at the 10^{-4} cancer risk level.

EPA excluded two categories of pollutants from further evaluation. First, EPA excluded pollutants that, when compared to the hazard index, presented no risk to human health at the highest concentration found in the 40-City Study or in other available data bases for each particular use or disposal practice. The hazard index developed for each pollutant and for each use or disposal practice was used to compare a pollutant's risk to the 1×10^{-6} risk level for carcinogens or to a threshold level index for noncarcinogens. Second, EPA deferred from consideration those pollutants for which there were insufficient data to conduct a risk assessment. Table 4-2 identifies the pollutants excluded or deferred under these two categories. Table 4-3 presents the 16 pollutants that remained for regulatory consideration for the surface disposal of sewage sludge at the time the proposed Part 503 rule was published on February 6, 1989. Following publication of the proposed rule, additional data available on the toxicity and environmental properties of chromium subsequent to its exclusion warranted that it be further evaluated. EPA conducted a more detailed risk assessment, therefore, on 17 pollutants (see Section Five), forming the basis for the limits for the three pollutants (arsenic, chromium, and nickel) in Part 503, Subpart C.

Although EPA believed that the 40-City Study data were the appropriate data on which to base the February 6, 1989, proposed Part 503 regulation, the Agency later concluded that the data needed to be replaced or, at a minimum, supplemented to support the final regulation.

TABLE 4-2

**POLLUTANTS EXCLUDED OR DEFERRED
FROM REGULATORY CONSIDERATION
FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE**

Pollutant	Reason
Chromium*	Excluded—no adverse effect on human health
Cobalt	Deferred—insufficient data for risk assessment
Cyanide	Excluded—no adverse effect on human health
2,4-Dichlorophenoxy-acetic acid	Excluded—no adverse effect on human health
Malathion	Excluded—no adverse effect on human health
Methylene chloride	Deferred—insufficient data for risk assessment
Methylene ketone	Deferred—insufficient data for risk assessment
Molybdenum	Excluded—no adverse effect on human health
Phenanthrene	Deferred—insufficient data for risk assessment
Phenol	Excluded—no adverse effect on human health
Selenium	Excluded—no adverse effect on human health
Zinc	Excluded—no adverse effect on human health

*Additional data available on the toxicity and environmental properties of chromium subsequent to this exclusion warranted that a risk assessment be performed and that a pollutant limit be developed.

TABLE 4-3

**POLLUTANTS EVALUATED FOR
SURFACE DISPOSAL OF SEWAGE SLUDGE
FOR THE PROPOSED PART 503 RISK ASSESSMENT**

Arsenic
Benzene
Benzo(a)pyrene
Bis (2-ethylhexyl) phthalate
Cadmium
Chlordane
Chromium
Copper
DDT/DDD/DDE
Lead
Lindane
Mercury
Nickel
n-Nitrosodimethylamine
PCBs
Toxaphene
Trichloroethylene

EPA therefore undertook the National Sewage Sludge Survey (NSSS)² to obtain a current and reliable data base for developing the final Part 503 regulation. The NSSS data base was used to develop the regulatory impact of the Part 503 regulation on existing sewage sludge use or disposal practices, to delete pollutants from regulation under Part 503, and to derive the nickel pollutant limit in Subpart C.

²The National Sewage Sludge Survey data collection effort began in August 1988 and was completed in September 1989. EPA collected sewage sludge samples at 180 publicly owned treatment works (POTWs) with either secondary or advanced treatment processes and analyzed them for more than 400 pollutants. In addition, through the use of detailed questionnaires, the survey collected information on sewage sludge use or disposal practices from 475 POTWs with at least secondary treatment of wastewater.

SECTION FIVE

PART 503 RISK ASSESSMENT METHODOLOGY FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE

This section describes the risk assessment methodology EPA used to further evaluate the 17 pollutants of concern discussed in Section Four to determine whether they posed a risk to human health and the environment and should be regulated under Part 503. Section 5.1 describes why EPA chose two prototype surface disposal units—a monofill and a surface impoundment—on which to conduct the risk assessment. Section 5.2 presents the general approach that EPA took to derive the risk-based pollutant criteria. The next two sections explain the methodology by which EPA conducted the risk assessment for the monofill prototype (Section 5.3) and the surface impoundment prototype (Section 5.4). Each section contains sample calculations for the pollutant criteria. The results of the risk assessment appear in Section 5.5. The risk assessment methodology is based on numerous references, some of which relate to technical criteria of ground water and air modeling and others relating directly to risk-based factors. The factors regarding risk methodology are discussed in Section 5.6, while technical parameters are summarized in tables in Section 5.7 and discussed fully in Section 5.8.

5.1 DESCRIPTION OF TWO MODEL PROTOTYPES OF SURFACE DISPOSAL SITES— MONOFILL AND SURFACE IMPOUNDMENT

The surface disposal of sewage sludge potentially can cause pollution of ground water and subsequent health risks to humans who use the ground water for drinking. It can also lead to the emission of volatile organic pollutants and result in risks to humans who are exposed to the pollutants and who inhale the contaminated air. The risk assessment conducted for the surface disposal of sewage sludge evaluates risk to a highly exposed individual (HEI) via these two pathways. Potential exposure of an HEI to pollution from nearby surface water bodies is not considered in this analysis because responsible management practices are assumed to control runoff.

EPA defines the term "surface disposal" broadly to include the disposal of sewage sludge in surface impoundments, waste piles, lagoons, sludge-only landfills (monofills), and dedicated sites (see Section Two). Within each category, surface disposal sites may differ further by site design and management practices. To account for the risk posed by sewage sludge placed in any one of these surface disposal sites, EPA calculated the risk from disposal of sewage sludge in two common surface disposal units—a surface impoundment and a monofill—and generalized the conditions at these sites. Two idealized prototypes, therefore, have been defined to represent this wide mix of surface disposal practices: a trench monofill and a surface impoundment with continuous inflow.

The monofill prototype is represented by a sewage sludge-only trench fill. Disposal involves the excavation of trenches so that dewatered sewage sludge may be directly deposited from a haul vehicle. Sewage sludge is entirely buried below the original ground surface. Only dewatered sewage sludges with solids contents greater than or equal to 20 percent are assumed to be suitable for disposal and the sewage sludge is often mixed with a bulking agent (e.g., soil) to increase solids content. Normal operating procedures require that the monofill be covered daily to reduce odors and provide vector (pest) control. In addition, a final cover is assumed to be placed on the monofill after closure.

The surface impoundment prototype is assumed to receive a continuous inflow of wastewater. A vertical outflow pipe maintains the surface level at a constant height and liquid is assumed to leave the impoundment both in the outflow and in seepage through the floor of the impoundment. Sewage sludge entering the impoundment is assumed to have a low solids content (between 2 and 5 percent). Over time, particulate settling occurs and a denser layer of sediment accumulates on the floor of the lagoon. Eventually, this layer of sediment extends to the top of the impoundment and no further inflow is possible. Upon closure, the sewage sludge is left permanently in place and remains uncovered.

One key difference between the surface impoundment and monofill prototypes is that the active surface impoundment is assumed to contain significantly more liquid than the active monofill. Seepage through the floor of the facility is therefore expected to be greater for a surface impoundment and may be sufficient to sustain a local "mounding" of the underlying water

table. The surface layer of the impoundment is also assumed to be in a liquid state over the active lifetime of the facility. The volatilization of organic pollutants from this liquid layer is therefore expected to differ from volatilization predicted for a monofill since the monofill is assumed to contain a higher percentage of solids and to receive a daily and eventually a permanent soil cover.

5.2 GENERAL APPROACH USED TO DERIVE RISK-BASED POLLUTANT CRITERIA

For each surface disposal prototype (monofill and surface impoundment), risk-based pollutant criteria are derived separately for the vapor and ground-water pathways of exposure. Calculations, however, have been integrated so that pollutant mass is conserved, meaning that the total mass of pollutant loss is equal to the sum of losses to ground water, vapor, degradation, and, for surface impoundments, outflow. The ground-water pathway criteria are limited to a 300-year time horizon; pollutant concentrations that may occur in well water after 300 years are ignored. For organic pollutants, the maximum predicted 70-year average ambient air concentration is used to derive criteria for the vapor pathway. EPA derived the risk-based pollutant criteria by following four steps:

- 1) prepare a "mass balance" of pollutant loss by calculating the relative rates at which the pollutant is removed from the site by leaching to ground water, volatilization to air, degradation, and, for surface impoundments, outflow;
- 2) determine the reference concentration of the pollutant in ground water or air;
- 3) determine the pollutant concentration in each medium resulting from a unit concentration (mg/kg dry weight) in sewage sludge at the site; and
- 4) derive the reference concentration of the pollutant in sewage sludge (e.g., the pollutant criteria) by dividing the reference concentration of the pollutant in ground water or air by the pollutant concentration predicted per unit concentration in sewage sludge.

5.2.1 Mass Balance

EPA developed the risk assessment methodology to account for the multiple partitioning of each pollutant concentration. All losses are treated as first-order and a rate-loss coefficient is calculated for each scenario. Calculations for the monofilling of sewage sludge account for leaching to ground water, volatilization, and pollutant degradation. For surface impoundments, pollutant losses include leaching to ground water, volatilization, pollutant degradation, and effluent or water discharge.

5.2.2 Modeling of Ground-Water Contamination

The risk assessment methodology for the surface disposal of sewage sludge evaluated the risk from drinking contaminated water from different classes of ground water (Class I, II, or III) according to EPA's ground-water classification system. Risk-based criteria (see Section 5.6) were developed for both Class I and Class II/III ground water. However, after completing the risk assessment, EPA determined that it would be more appropriate to treat all ground water as drinkable in accordance with EPA's Class II designation in the development of pollutant limits for the final Part 503 regulation.

For the risk assessment, EPA modeled ground-water pollution near surface disposal sites using a computer code consisting of linked versions of VADOFT and AT123D. The VADOFT module simulates the flow of both water and pollutants through the unsaturated soil zone. The AT123D component simulates the lateral movement of pollutants through the saturated soil zone. For surface-disposal facilities, EPA assumed that no individual on-site drank well water and that the property boundary (fenceline) extended 150 meters (m) beyond the edge of the surface disposal site. For all sites, the depth to ground water is conservatively assumed to be one meter; although typical depths for actual sites are much greater. EPA calculated the maximum pollutant concentrations estimated within the first 300 years at 150 m in the downgradient direction from each surface disposal prototype facility and used these concentrations to derive criteria based on the reference drinking water concentration. The pollutant criteria correspond to the concentration of a given pollutant received by an HEI who consumes two liters of

contaminated ground water per day at a cancer risk level of 10^{-4} . Every HEI exposed to this concentration of pollutant faces a one in 10,000 lifetime risk of contracting cancer as a result.

EPA derived separate pollutant criteria for lined and unlined monofills and surface impoundments for a Class I aquifer and a Class II or III aquifer. To derive pollutant limits for lined and unlined surface disposal sites, EPA used similar models, although some of the modeling assumptions are different. The main difference is that, for lined units, EPA assumed that an additional three foot clay layer is located between the facility bottom and the unsaturated zone. The effect of the liner on pollutant transport into ground water is a function of the hydraulic conductivity of the liner, which is expected to reduce the net recharge to the aquifer, and the additional vertical distance between the facility bottom and the water table. These factors tend to reduce pollutant flux to ground water and increase volatilization.

5.2.3 Modeling the Contamination of Ambient Air

The volatile emission of pollutants from surface disposal facilities differs according to the type of facility being considered. For the surface impoundment prototype, emissions can occur from the impoundment's liquid surface, which remains uncovered throughout the life of the facility. For the monofill prototype, volatile emissions occur from a mixture of sewage sludge and soil and are limited by the application of a daily and, ultimately, a permanent layer of soil cover. Volatile emissions from the liquid surface of the surface impoundment prototype are modeled with a two-film resistance model (Thomann and Mueller, 1987). Emissions from the monofill prototype are estimated with a model described in U.S. EPA (1986d), which calculates these emissions for both uncovered monofill cells and for those protected by daily and permanent cover. A weighted average of these estimates is used to predict total average volatile emissions to which an HEI would be exposed.

After estimating the emissions, EPA calculates the expected concentrations of pollutants in ambient air based on a conservative simplification of the ISCLT model (Bowers et al., 1980) as discussed in Environmental Science and Engineering (1985) and U.S. EPA (1986d). Concentrations are estimated at the property boundary (150 m from the edge of the site) and are

used to derive pollutant limits for an HEI who inhales contaminated air at a rate of 20 cubic meters per day with a lifetime exposure based on a risk level of 10^{-4} .

5.2.4 Exposure Scenarios

To derive the risk-based pollutant criteria for the surface disposal of sewage sludge established in the Part 503 regulation, EPA evaluated 10 exposure scenarios. These scenarios account for exposure to pollutants from sewage sludge placed in lined or unlined surface impoundments or monofills. In addition, these scenarios are all based on one of the two pathways: inhalation of volatile emissions or ingestion of contaminated ground water (Class I or Class II/III). These exposure scenarios are listed below:

- Scenario 1: Sludge-soil-air-human (fumes from volatile pollutants in monofilled sewage sludge)
- Scenario 2: Sludge-soil-air-human (fumes from volatile pollutants in sewage sludge placed in a surface impoundment)
- Scenario 3: Sludge-soil-ground water (water from wells near a monofill without a liner and leachate collection system: Class I aquifer)
- Scenario 4: Sludge-soil-ground water (water from wells near a surface impoundment without a liner and leachate collection system: Class I aquifer)
- Scenario 5: Sludge-soil-ground water (water from wells near a monofill with a liner and leachate collection system: Class I aquifer)
- Scenario 6: Sludge-soil-ground water (water from wells near a surface impoundment with a liner and leachate collection system: Class I aquifer)
- Scenario 7: Sludge-soil-ground water (water from wells near a surface impoundment without a liner and leachate collection system: Class II or III aquifer)
- Scenario 8: Sludge-soil-ground water (water from wells near a surface impoundment without a liner and leachate collection system: Class II or III aquifer)
- Scenario 9: Sludge-soil-ground water (water from wells near a monofill with a liner and leachate collection system: Class II or III aquifer)

Scenario 10: Sludge-soil-ground water (water from wells near a surface impoundment with a liner and leachate collection system: Class II or III aquifer)

5.2.5 Uncertainties and Limitations

To obtain an estimate of risk from placing sewage sludge on a surface disposal site, EPA simplified calculations by deciding on numerous assumptions, almost all of which are conservative. True exposure and risk will differ from the estimates provided here depending on the extent to which actual conditions at each site differ from those that are assumed in the models. For example, if the local depth to ground water exceeds 1 m or if the hydraulic conductivity of the local soil medium is less than that of sand, actual pollution of ground water beneath the surface disposal site is likely to be lower than that calculated for this risk assessment. Similarly, concentrations in ground water at distances greater than 150 m and in directions other than downgradient are likely to be lower than those calculated for this analysis. On the other hand, a nonhomogeneous or fractured medium beneath a surface disposal facility might lead to the pollution of ground water at higher concentrations than those predicted by the VADOFT and AT123D models.

5.3 RISK ASSESSMENT METHODOLOGY FOR MONOFILL PROTOTYPE

EPA derived the risk-based pollutant criteria for sewage sludge placed in a monofill prototype according to the following four basic steps:

- 1) prepare a "mass balance" of pollutant loss, which involves calculating the individual and combined rates at which the pollutant is removed from the site by competing loss processes;
- 2) determine the reference concentration of pollutant in the medium of concern for each exposure pathway;
- 3) determine the relationship between the pollutant concentrations in the environmental media and the pollutant concentrations in the sewage sludge deposited in the monofill; and

- 4) combine the results from Steps (1) through (3) to calculate the pollutant criteria.

5.3.1 Methodology for Mass Balance

EPA assumed that pollutants enter the monofill facility through daily deposits of sewage sludge and are removed through degradation, leaching, and volatilization. Rates of pollutant loss are assumed to be proportional to the residual concentration of pollutants in the monofill, and mass balance calculations begin by estimating first-order loss coefficients for each competing loss process.

5.3.1.1 Pollutant Losses Through Leaching

EPA calculated a coefficient for the rate of pollutant loss to leaching by assuming that pollutant mass in a filled monofill cell is partitioned between dissolved and adsorbed phases and that this partition is at equilibrium. Based on mathematical relationships discussed in Appendix B, the concentration of pollutants dissolved in water within the monofill can be estimated from the total concentration of pollutants within the facility:

$$C_{loc} = \frac{C_t}{BD \cdot KD + \theta_w + \dot{H} \theta_a} \quad (1)$$

where:

$$\dot{H} = \frac{H}{RT} \quad (2)$$

and:

C_{loc}	=	concentration of pollutants in water-filled pore space of soil (kg/m ³)
C_t	=	total concentration of pollutants in soil (kg/m ³)
BD	=	bulk density of sewage sludge/soil mixture (kg/m ³)
KD	=	equilibrium partition coefficient for the pollutant (m ³ /kg)
θ_w	=	water-filled porosity of sewage sludge/soil mixture (unitless)
\dot{H}	=	nondimensional Henry's Law constant for the pollutant
θ_a	=	air-filled porosity of sludge/soil (unitless)
H	=	Henry's Law constant for the pollutant (atm•m ³ /mol)
R	=	ideal gas constant (8.21x10 ⁻⁵ m ³ •atm/mol•K)
T	=	temperature (K)

As discussed in Appendix C, the flux of pollutant mass leaching from treated soil can be calculated as the product of net ground-water recharge times the estimated concentration of pollutant in leachate. This flux can then be divided by total pollutant mass per unit area to obtain the first-order loss coefficient for leaching as follows:

$$K_{lec} = \frac{NR}{(BD \cdot KD + \theta_w + \bar{H} \theta_a) d_f} \quad (3)$$

where:

K_{lec}	=	loss rate coefficient for leaching (yr ⁻¹)
NR	=	annual recharge to ground water beneath the monofill (m/yr)
BD	=	bulk density of sewage sludge/soil mixture (kg/m ³)
KD	=	equilibrium partition coefficient for the pollutant (m ³ /kg)
θ_w	=	water-filled porosity of sewage sludge/soil mixture (unitless)
\bar{H}	=	nondimensional Henry's Law constant for the pollutant
θ_a	=	air-filled porosity of sewage sludge/soil mixture (unitless)
d_f	=	depth of a monofill cell (m)

5.3.1.2 Pollutant Losses to Volatilization

Rates of volatilization from a filled cell in a sewage sludge monofill will vary according to whether a cover layer of soil has been applied. EPA assumed that each cell in the monofill contains uncovered sewage sludge for a few hours on each of the days it receives sewage sludge. Following each deposit, a temporary cover layer of soil is applied. Once the monofill's capacity is exhausted, a thicker permanent cover of soil is applied to the entire facility (U.S. EPA, 1986d). A time-weighted average of emission rates with and without cover is, therefore, used to describe the average rate of volatile emissions for an individual cell in the monofill. The fraction of the facility's active lifetime that a typical cell will be uncovered is calculated as:

$$f_{un} = \frac{t_{un}}{LF} \quad (4)$$

where:

f_{un}	=	fraction of facility's active lifetime that a typical cell contains sewage sludge without soil cover (unitless)
t_{un}	=	time that each individual monofill cell contains uncovered sewage sludge (yr)
LF	=	active lifetime of monofill (yr)

Some monofill cells will be filled early in the facility's operation, while others become filled closer to facility closure. The average monofill cell will contain sewage sludge for half the active lifetime of the facility. The fraction of the facility's active lifetime that such a cell will contain sewage sludge protected by temporary cover is:

$$f_{co} = \frac{1}{2} - f_{un} \quad (5)$$

where:

- f_{co} = fraction of facility's active lifetime that typical cell contains sewage sludge with temporary soil cover
 f_{un} = fraction of facility's active lifetime that a typical cell contains sewage sludge without soil cover (yr)

EPA calculated a time-weighted average rate of emissions for a typical monofill cell using equations describing emissions from cells with and without soil cover. Equations describing rates of volatile emissions from covered and uncovered landfill cells were estimated by Environmental Science and Engineering (1985) as discussed in U.S. EPA (1986d). Within each of these equations, presented below, there are unitless numerical constants which resulted from the initial estimation process. It must be noted that such constants in these and other equations from this source (used further below) cannot be given any precise definitions.

The equation estimating the rate of emissions from an uncovered landfill cell is:

$$q_{un} = \frac{0.17 \omega 0.994^{(T-293)} C_a}{\sqrt{MW}} \quad (6)$$

where:

- q_{un} = emission rate from treated soil for uncovered period ($\text{kg/m}^2 \cdot \text{sec}$)
0.17 = empirical constant transferred from the literature source of the equation
 ω = wind speed (m/sec)
0.994 = empirical constant transferred from the literature source of the equation
T = temperature (K)
 C_a = vapor concentration of pollutant in air-filled pore space of treated soil (kg/m^3)
293 = 15°C (converted to K)
MW = molecular weight of pollutant (g/mole)

For a landfill cell with soil cover, the estimated equation is:

$$q_{\infty} = \frac{9.2 \times 10^{-5} \theta_a^{(10/3)} 1.006^{(T-293)} C_a}{\sqrt{MW} d_c \theta_a^2} \quad (7)$$

where:

- q_{∞} = emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
- 9.2×10^{-5} = numerical constant
- θ_a = air-filled porosity in cover layer of soil (unitless)
- 1.006 = numerical constant
- T = temperature (K)
- 293 = 15°C (converted to K)
- C_a = concentration of pollutant in air-filled pore space of sewage sludge/soil mixture (kg/m^3)
- MW = molecular weight of pollutant (g/mole)
- d_c = depth of cover (m)
- θ_a = total porosity of cover layer (unitless)

Equations 6 and 7 are based on the concentration of the pollutant in air-filled pore-space within the monofill. As explained in Appendix B, this concentration can be related to the total concentration of pollutant in the sewage sludge/soil mixture as:

$$C_a = \frac{C_t}{\frac{BD \cdot KD}{\dot{H}} + \frac{\theta_w}{\dot{H}} + \theta_a} \quad (8)$$

where:

- C_a = concentration of pollutant in air-filled pore space of sewage sludge/soil mixture (kg/m^3)
- C_t = total concentration of pollutant in sewage sludge/soil mixture (kg/m^3)
- BD = bulk density of sewage sludge/soil mix (kg/m^3)
- KD = equilibrium partition coefficient for pollutant (m^3/kg)
- \dot{H} = Henry's Law constant (unitless at specified temperature)
- θ_w = water-filled porosity in sewage sludge/soil mixture (unitless)
- θ_a = air-filled porosity in sewage sludge/soil mixture (unitless)

EPA combined estimated emissions from both an uncovered and a temporarily covered monofill cell to derive a time-weighted average rate of emissions from a monofill cell during the facility's active lifetime:

$$q_{ac} = q_{un} f_{un} + q_{co} f_{co} \quad (9)$$

where:

- q_{ac} = time-weighted average rate of emissions from typical monofill cell over the active lifetime of the monofill ($\text{kg/m}^2 \cdot \text{sec}$).
- q_{un} = rate of pollutant volatilization from an uncovered monofill cell ($\text{Kg/m}^2 \cdot \text{sec}$)
- f_{un} = fraction of monofill's active lifetime that typical cell contains uncovered sewage sludge
- q_{co} = emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
- f_{co} = fraction of facility's active lifetime that typical cell contains sewage sludge with temporary soil cover

By dividing the above estimated loss rate for volatile emissions by total pollutant mass per unit area in the filled monofill, EPA obtained a first-order loss rate coefficient:

$$K_{va} = \frac{q_{ac} 3.16 \times 10^7}{d_f C_t} \quad (10)$$

where:

- K_{va} = first-order loss rate coefficient for volatilization during facility's active operation (yr^{-1})
- q_{ac} = time-weighted average rate of emissions from typical monofill cell over the active lifetime of the monofill ($\text{kg/m}^2 \cdot \text{sec}$)
- 3.16×10^7 = conversion factor (sec) (yr^{-1})
- d_f = depth of a monofill cell (m)
- C_t = total concentration of pollutant in sewage sludge/soil mixture (kg/m^3)

In this equation, total pollutant mass is calculated by multiplying the depth of the monofill cell by the total pollutant concentration.

Estimated coefficients for losses to volatilization and leaching are combined with an assumed coefficient for losses to degradation (obtained from scientific literature) to yield a "lumped" coefficient describing pollutant loss through all three pathways during the facility's active lifetime:

$$K_{ta} = K_{lec} + K_{va} + K_{deg} \quad (11)$$

where:

- K_{ta} = coefficient for total rate of pollutant loss through leaching, volatilization, and degradation during facility's active operation (yr^{-1})

- K_{lec} = rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
 K_{va} = rate coefficient for loss of pollutant to volatilization from active monofill (yr^{-1})
 K_{deg} = degradation rate coefficient for monofill (yr^{-1})

The fraction of the total rate of pollutant loss attributable to each individual process during the facility's active lifetime is then:

$$\begin{aligned}
 f_{la} &= \frac{K_{lec}}{K_{ta}} \\
 f_{va} &= \frac{K_{va}}{K_{ta}} \\
 f_{da} &= \frac{K_{deg}}{K_{ta}}
 \end{aligned} \tag{12}$$

where:

- f_{la} = fraction of total pollutant loss during facility's active operation attributable to leaching (unitless)
 K_{lec} = rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
 K_{ta} = coefficient for total rate of pollutant loss through leaching, volatilization, and degradation during facility's active operation (yr^{-1})
 f_{va} = fraction of total pollutant loss during facility's active operation attributable to volatilization (unitless)
 K_{va} = rate coefficient for loss of pollutant to volatilization from active monofill (yr^{-1})
 f_{da} = fraction of total pollutant loss during facility's active operation attributable to degradation (unitless)
 K_{deg} = rate coefficient for loss of pollutant to degradation from monofill (yr^{-1})

The fraction of total pollutant loading lost over the facility's active lifetime is calculated as follows:

$$f_{sc} = 1 - \frac{M_{LF}}{LF} \tag{13}$$

where:

- f_{sc} = fraction of total pollutant lost during monofill's active lifetime (unitless),
 M_{LF} = mass of pollutant in soil at end of active lifetime of monofill (kg/ha)
 LF = active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)

The variable M_{LF} is a function of the lumped rate of pollutant loss and is evaluated as:

$$\begin{aligned} M_t &= 0 & (t=0) \\ M_t &= [M_{t-1} + 1] e^{-K_u} & (1 \leq t \leq LF) \end{aligned} \quad (14)$$

where:

M_t = mass of pollutant in soil at end of year t (kg/ha)
 LF = active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)
 K_u = coefficient for total rate of pollutant loss through leaching, volatilization and degradation during facility's active operation (yr^{-1})

Once the facility's capacity is exhausted, a permanent cover layer of soil is applied to its surface. This permanent cover reduces the rate of volatilization, changing both the total rate of pollutant loss and the fraction of that loss attributable to volatilization, leaching, or degradation. Based on the increased thickness of cover, EPA calculated an estimated rate of volatilization from the inactive monofill (K_{vi}) with Equations 9 and 10 by setting f_{va} to zero. Rate coefficients for loss to leaching and degradation were assumed to be unaffected by soil cover, so the lumped rate of loss for the inactive monofill is described by:

$$K_{ti} = K_{lec} + K_{vi} + K_{deg} \quad (15)$$

where:

K_{ti} = coefficient for total rate of pollutant loss from inactive monofill (yr^{-1})
 K_{lec} = coefficient for rate of pollutant loss through leaching from monofill (yr^{-1})
 K_{vi} = coefficient for rate of pollutant loss through volatilization from inactive monofill (yr^{-1})
 K_{deg} = coefficient for rate of pollutant loss through degradation from monofill (yr^{-1})

The fraction of loss attributable to each individual process is calculated as:

$$\begin{aligned}
 f_{li} &= \frac{K_{lec}}{K_{di}} \\
 f_{vi} &= \frac{K_{vi}}{K_{di}} \\
 f_{di} &= \frac{K_{deg}}{K_{di}}
 \end{aligned}
 \tag{16}$$

where:

f_{li}	=	fraction of total pollutant loss from inactive monofill attributable to leaching (unitless)
K_{lec}	=	rate coefficient for loss of pollutant to leaching from monofill (yr ⁻¹)
K_{di}	=	coefficient for total rate of pollutant loss from inactive monofill (yr ⁻¹)
f_{vi}	=	fraction of total pollutant loss from inactive monofill attributable to volatilization (unitless)
K_{vi}	=	coefficient for rate of pollutant loss through volatilization from inactive monofill (yr ⁻¹)
f_{di}	=	fraction of pollutant loss from inactive monofill that is lost to degradation (unitless)
K_{deg}	=	coefficient for rate of pollutant loss through degradation from monofill (yr ⁻¹)

As discussed below, EPA used these fractions and the lumped rate coefficients for pollutant loss to derive criteria for the vapor and ground-water pathways.

5.3.2. Methodology for Ground-Water Pathway

Derivations of pollutant limits for the ground-water pathway began with the calculation of an adjusted reference water concentration for each pollutant of concern. EPA calculated this value from the maximum pollutant level (MCL) by subtracting an estimated background concentration of the pollutant in ground water:

$$RC_{gw} = MCL - C_b \tag{17}$$

where:

RC_{gw}	=	adjusted reference water concentration (mg/l)
MCL	=	maximum pollutant level (mg/l)

C_b = average background concentration of pollutant in drinking water from wells (mg/l)

Alternatively, if no MCL is available, the adjusted reference water concentration is calculated (for carcinogenic pollutants) from a selected risk level and a human cancer potency:

$$RC_{gw} = \frac{RL \ BW}{q_1 \ RE \ I_w} \quad (18)$$

where:

RC_{gw} = reference concentration for pollutant in ground water (mg/l)
 RL = risk level (incremental risk of cancer per lifetime, unitless)
 BW = human body weight (kg)
 q_1 = human cancer potency (mg/kg•day)⁻¹ or (kg•day/mg)
 RE = relative effectiveness of exposure through ingestion (unitless)
 I_w = total water ingestion rate (l/day)

5.3.2.1 Simulating Flow and Pollutant Transport Through Unsaturated and Saturated Soil Zones

In the next step, EPA used the reference water concentration of pollutant in well water to calculate a reference concentration of pollutant in seepage beneath the facility. Two mathematical models were combined to calculate an expected ratio between these two concentrations. The Vadose Zone Flow and Transport finite element module (VADOFT) from the RUSTIC model (U.S. EPA, 1989a,b) was used to estimate flow and transport through the unsaturated zone, and the AT123D analytical model (Yeh, 1981) was used to estimate flow and transport through the saturated zone.

VADOFT allows consideration of multiple soil layers, each with homogeneous soil characteristics. Within the unsaturated zone, the attenuation of organic pollutants is predicted based on longitudinal dispersion, an estimated retardation coefficient derived from an equilibrium partition coefficient, and a first-order rate of pollutant degradation. The model is executed in two steps; results from the unsaturated zone flow and transport module are passed as input to the saturated zone module. The input requirements for the unsaturated zone module include various site-specific and geologic parameters and the leaching rate from the bottom of

the monofill. It is assumed that the flux of pollutant mass into the top of the unsaturated zone beneath a facility can be represented by results from the mass-balance calculations described above. Results from analysis of the unsaturated zone give the flow velocity and concentration profiles for each pollutant of interest. These velocities and concentrations are evaluated at the water table, converted to mass fluxes for each pollutant, and then these fluxes are used as input to the saturated zone module.

The flow system in the vertical column is solved with VADOFT, which is based on an overlapping representation of the unsaturated and saturated zones. The water flux at the soil/liquid interface is specified for the bottom of the impoundment, which defines the top of the unsaturated zone in the model. In addition, a constant pressure-head boundary condition is specified for the bottom of the unsaturated zone beneath the lagoon. This pressure-head is chosen to be consistent with the expected pressure head at the bottom of the saturated zone, without consideration of the added flux leaching from sewage sludge in the monofill. Transport in the unsaturated zone is determined using the Darcy velocity (V_d) and saturation profiles from the flow simulation. From these, the transport velocity profile can be determined.

Although limited to one-dimensional flow and transport, the use of a rigorous finite-element model in the unsaturated zone allows consideration of depth-variant physical and chemical processes that would influence the mass flux entering the saturated zone. Among the more important of these processes are advection (which is a function of the Darcy velocity, saturation and porosity), mass dispersion, adsorption of the leachate onto solids, and both chemical and biological degradation.

To represent the variably saturated soil column beneath the floor of the monofill, the model discretizes the column into a finite-element grid consisting of a series of one-dimensional elements connected at nodal points. Elements can be assigned different properties for the simulation of flow in a heterogeneous system. The model generates the grid from user-defined zones; the user defines the homogeneous properties of each zone, the zone thickness and the number of elements per zone, and the code automatically divides each zone into a series of elements of equal length. The governing equation is approximated using the Galerkin finite element method and then solved iteratively for the dependent variable (pressure-head) subject to

the chosen initial and boundary conditions. Solution of the series of nonlinear simultaneous equations generated by the Galerkin scheme is accomplished by either Picard iteration, a Newton-Raphson algorithm or a modified Newton-Raphson algorithm. Once the finite-element calculation converges, the model yields estimated values for all the variables at each of the discrete nodal points. A detailed description of the solution scheme is found in U.S. EPA (1989a).

One-dimensional advective-dispersive transport is estimated with VADOFT based on the estimated mass flux of pollutant into the top of the soil column, and a zero concentration boundary condition at the bottom of the saturated zone. Sewage sludge is assumed to be deposited in the monofill for 20 years, followed by an inactive period in which pollutant is depleted from the monofill by leaching and volatilization. To simulate potential pollution of ground water, the loading of pollutant into the unsaturated zone beneath the monofill is "linearized" into a pulse of constant magnitude to represent the maximum annual loss of pollutant (kg/ha-yr) occurring over the 300-year simulation period modeled. The duration of that pulse is calculated so that pollutant mass is conserved. For monofills, the rate of maximum total pollutant loss (kg/yr) will occur in the year immediately following the last deposit of sewage sludge since the total mass of pollutant at the site reaches its peak at that time. As explained in Appendix C, this peak rate of loss could be maintained for a maximum length of time described by:

$$TP = \frac{LF}{1 - e^{(-K_a LF)}} \quad (19)$$

where:

- TP = length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant applied to site (yr)
- LF = active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)
- K_a = rate coefficient for total loss of pollutant during monofill's active lifetime (yr^{-1})

This result is used to prepare inputs for VADOFT, which predicts the concentration of pollutant at the water table. The mass flux of pollutant into the saturated zone is evaluated at the water table based on the derived concentration distribution and the Darcy velocity. The

resulting mass flux from the VADOFT simulation is used as input for the AT123D model, which simulates pollutant transport through the saturated zone. It is represented as a mass flux boundary condition applied over a rectangular area representative of the facility's air-exposed surface. The transient nature of the flux is represented by time-dependent levels interpolated from the results generated by the VADOFT simulation of the unsaturated zone.

AT123D estimates the transport of pollutant through the saturated soil zone. As in calculations for the unsaturated zone, degradation of organic pollutants is assumed to be first-order during transport through the aquifer. Speciation and complexation reactions are ignored for metals, leading to the possible over- or underestimation of expected concentrations of metals in ground water at the location of a receptor well. Detailed descriptions of the AT123D model are provided by Yeh (1981) and will not be repeated here. In general, the model provides an analytical solution to the basic advective-dispersive transport equation. One advantage of AT123D is its flexibility: the model allows the user up to 450 options and is capable of simulating a wide variety of configurations of source release and boundary conditions.

For the current application, AT123D uses the source term and other input parameters to predict concentrations of pollutant within 300 years in a receptor well at the downgradient edge of the site (based on a unit concentration of 1 mg/l in leachate from the monofill). The ratio of these two concentrations is then:

$$f_{wel} = \frac{C_{wel}}{C_{lec}} \quad (20)$$

where:

f_{wel}	=	ratio of predicted concentration in well to concentration in leachate (unitless)
C_{wel}	=	predicted concentration of the pollutant in well (mg/l)
C_{lec}	=	unit concentration of the pollutant in leachate (1 mg/l)

Because calculations in both the VADOFT and AT123D components of the ground-water pathway model are linear with respect to the pollutant concentration in leachate beneath the site, this ratio can be used to back-calculate a reference concentration of pollutant in leachate:

$$RC_{lec} = \frac{RC_{gw}}{f_{wel}} \quad (21)$$

where:

- RC_{lec} = reference concentration of pollutant in leachate from the sewage sludge monofill (mg/l)
- RC_{gw} = reference concentration for pollutant in ground water (mg/l)
- f_{wel} = ratio of predicted concentration in well to concentration in leachate (unitless)

Next, multiplying this reference concentration (in mg/l) by the assumed net recharge (in m/yr) and adjusting units yields the reference flux of pollutant mass from the site.

$$RF_{gw} = 10 RC_{lec} NR \quad (22)$$

where:

- RF_{gw} = reference annual flux of pollutant to the unsaturated soil zone beneath the surface disposal facility (kg/ha•yr)
- 10 = conversion factor (kg/ha) ([mg•m]/l)⁻¹
- RC_{lec} = reference concentration for pollutant in leachate from sewage sludge monofill (mg/l)
- NR = net recharge (m/yr)

This allowable flux must be related to the pollutant dry-weight concentration in sewage sludge deposited in the monofill. Using the variables f_{la} (which describes the maximum fraction of total pollutant mass lost from the monofill through leaching) and TP (which provides an estimate for the minimum amount of time required to release all significant pollutant), the reference flux can be converted to an equivalent dry-weight concentration in sewage sludge:

$$RCS = \frac{TP RF_{gw} 10^6}{f_{la} SC} \quad (23)$$

where:

- RCS = reference dry-weight concentration of pollutant in sewage sludge (mg/kg)
- TP = length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant at site (yr)
- RF_{gw} = reference annual flux of pollutant to the unsaturated soil zone beneath the surface disposal facility (kg/ha•yr)
- 10⁶ = conversion factor (kg)(mg)⁻¹
- f_{la} = fraction of pollutant loss during monofill's active lifetime that is lost to leaching (unitless)

SC = estimated dry mass of sewage sludge contained in one hectare of completed monofill (kg/ha)

The dry mass of sewage sludge contained in one hectare of completed monofill is calculated by multiplying the facility's depth by the fraction of its volume containing pure sewage sludge and the mass of solids per cubic meter of sewage sludge:

$$SC = d_f f_{sl} MS 10^4 \quad (24)$$

where:

SC = estimated mass of dry sewage sludge contained in one hectare of completed monofill (kg/ha)
 d_f = depth of a monofill cell (m)
 f_{sl} = fraction of monofill's total volume containing pure sewage sludge (m^3/m^3 or unitless)
MS = mass of solids in 1 m^3 of pure sewage sludge (kg/m^3)
 10^4 = conversion factor (m^2) (ha)⁻¹

and:

$$MS = \frac{f_{sol} \rho_{sl} \rho_w}{f_{sol} \rho_w + (1 - f_{sol}) \rho_{sl}} \quad (25)$$

where:

MS = mass of solids in 1 m^3 of pure sewage sludge (kg/m^3),
 f_{sol} = fraction of solids in sewage sludge (kg/kg)
 ρ_{sl} = particle density of sewage sludge (kg/m^3)
 ρ_w = density of water (kg/m^3)

5.3.3 Methodology for Vapor Pathway

Calculations of pollutant criteria for the vapor pathway begin with derivations of reference air concentrations for each pollutant. Because all the pollutants under consideration for this pathway are considered carcinogenic, the reference air concentration is calculated as:

$$RC_{air} = \frac{RL \ BW \ 1000}{I_a \ q_1} \quad (26)$$

where:

RC_{air} = reference air concentration for pollutant ($\mu g/m^3$)
RL = risk level (incremental risk of cancer per lifetime)

BW	=	average body weight (kg)
1000	=	conversion factor (μg) (mg) ⁻¹
I _a	=	inhalation volume (m^3/day)
q ₁	=	human cancer potency ($\text{mg}/\text{kg}\cdot\text{day}$) ⁻¹

The next step is to relate releases of volatilized pollutant to expected concentrations in ambient air. The model used to simulate transport of volatilized pollutant from a surface disposal site is described by U.S. EPA (1986d) and is based on equations provided by Environmental Science and Engineering (1985). The highly exposed individual (HEI) is assumed to live at the downwind property boundary of the monofill site. A source-receptor ratio is calculated to relate the concentration of pollutant in ambient air at the HEI's location (g/m^3) to the rate at which that pollutant is emitted from the facility ($\text{g}/\text{m}^2\cdot\text{sec}$).

$$\text{SRR} = 2.032 \frac{A v}{(r' + x_y) \omega \sigma_z} \quad (27)$$

where:

SRR	=	source-receptor ratio (sec/m)
2.032	=	empirical constant transferred from the literature source of the equation
A	=	area of monofill (m^2)
v	=	vertical term (unitless)
r'	=	distance from the center of monofill to receptor (m)
x _y	=	lateral virtual distance (m)
ω	=	wind speed (m/sec)
σ _z	=	standard deviation of the vertical distribution of concentration (m)

The vertical term (v) is a function of source height, the mixing layer height, and σ_z. Under stable conditions the mixing layer height is assumed infinite, and for a pollutant release height of zero, v=1. The lateral virtual distance is the distance from a virtual point source to the monofill such that the angle θ subtended by the monofill's width is 22.5°. This distance is calculated as:

$$x_y = \sqrt{\frac{A}{\pi}} \cot \frac{\theta}{2} \quad (28)$$

where:

x _y	=	lateral virtual distance to receptor location (m)
A	=	surface area of surface disposal facility (m^2)
θ	=	angle subtended by width of disposal site at distance equal to estimated virtual distance from site (degrees)

The standard deviation of the vertical distribution of concentration (σ_z) is defined by an atmospheric stability class and the distance from the center of the monofill to the receptor. Based on values for parameters a and b listed for stable atmospheric conditions in Table 5-1, σ_z is calculated as:

$$\sigma_z = a x^b \quad (29)$$

where:

σ_z = standard deviation of the vertical distribution of concentration (m)
 a = first coefficient for calculating σ_z
 x = distance from center of monofill to receptor (km)
 b = second coefficient for calculating σ_z and:

$$x = 0.001 r' \quad (30)$$

where:

x = distance from center of monofill to receptor (km)
 0.001 = conversion factor (km) (m)⁻¹
 r' = distance from center of sewage sludge disposal facility to HEI's location (m)

The source-receptor ratio is combined with the reference air concentration to calculate a reference annual flux of pollutant:

$$RF_{air} = \frac{316 RC_{air}}{SRR} \quad (31)$$

where:

RF_{air} = reference annual flux of pollutant emitted from the site (kg/ha•yr)
 316 = conversion factor ($\mu\text{g}/\text{m}^2 \cdot \text{sec}$) (kg/ha•yr)⁻¹
 RC_{air} = reference concentration for pollutant in air ($\mu\text{g}/\text{m}^3$)
 SRR = source-receptor ratio (sec/m)

The reference pollutant concentration in sewage sludge is calculated by considering the maximum fraction of total pollutant mass expected to volatilize during the assumed timespan of a human life. This period spans both the active and inactive phases of the monofill's operation. Thus, the formula is:

TABLE 5-1
PARAMETERS USED TO CALCULATE σ_z *

Pasquill Stability Category	x (km)	a	b
Stable	0.10 - 0.20	15.209	0.81558
	0.21 - 0.70	14.457	0.78407
	0.71 - 1.00	13.953	0.68465
	1.01 - 2.00	13.953	0.63227
	2.01 - 3.00	14.823	0.54503
	3.01 - 7.00	16.187	0.46490
	7.01 - 15.00	17.836	0.41507
	15.01 - 30.00	22.651	0.32681
	30.01 - 60.00	27.084	0.27436
	> 60.00	34.219	0.21716

* σ_z calculated as $\sigma_z = ax^b$ where x is distance in km.

Source: Environmental Science and Engineering (1985).

$$f_{vis} = f_{va} f_{ac} + f_{vi} (1 - f_{ac}) [1 - e^{-K_{di}(LS-LF)}] \quad (32)$$

where:

- f_{vis} = fraction of pollutant mass which volatilizes over a human lifetime (unitless)
- f_{va} = fraction of pollutant loss during monofill's active lifetime that is lost to volatilization (unitless)
- f_{ac} = fraction of total pollutant loading lost during active operation of monofill facility (unitless)
- f_{vi} = fraction of total pollutant loss from inactive monofill attributable to volatilization (unitless)
- K_{di} = rate coefficient for total loss of pollutant from inactive monofill (yr^{-1})
- LS = lifespan of average individual (yr)
- LF = active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)

This result is combined with the reference annual flux of pollutant (Equation 31) and the estimated mass of dry sewage sludge per hectare of monofill (Equation 24) to calculate a reference concentration of pollutant in monofilled sewage sludge:

$$RCS = \frac{RF_{air} LS 10^6}{f_{vis} SC} \quad (33)$$

where:

- RCS = reference concentration of pollutant in sewage sludge for the volatilization pathway (mg/kg dry weight)
- RF_{air} = reference annual flux of pollutant to air above the site ($\text{kg/ha} \cdot \text{yr}$)
- LS = lifespan of average individual (yr)
- 10^6 = conversion factor (mg) (kg) $^{-1}$
- f_{vis} = fraction of pollutant mass which volatilizes over a human lifetime (unitless)
- SC = mass of sewage sludge contained in one hectare of surface disposal facility (kg/ha)

5.3.4 Monofill Prototype Sample Calculations for Pollutant Criteria

5.3.4.1 Mass Balance Calculations

The methodology described above is illustrated with sample calculations for benzene. Sample calculations are described to two significant figures, except in cases where additional precision further clarifies the methodology. Actual calculations are performed with eight-byte "double" precision, leading to occasional discrepancies between actual results and the calculations described here.

5.3.4.1.1 Pollutant Losses Through Leaching

A coefficient for the rate at which benzene is lost to leaching is calculated as:

$$\begin{aligned} K_{lec} &= \frac{NR \text{ (m/yr)}}{[BD \text{ (kg/m}^3) \text{ KD (m}^3\text{/kg)} + \theta_w + \bar{H} \theta_a] d_f \text{ (m)}} \\ &= \frac{(0.5)}{[(1400)(0.033) + (0.2) + (0.23)(0.2)](3.46)} \\ &= 0.0031 \text{ (yr}^{-1}\text{)} \end{aligned} \tag{34}$$

where:

K_{lec}	=	loss rate coefficient for leaching (yr ⁻¹)
NR	=	annual recharge to ground water beneath the monofill (m/yr)
BD	=	bulk density of sewage sludge/soil mixture (kg/m ³)
KD	=	equilibrium partition coefficient for the pollutant (m ³ /kg)
θ_w	=	water-filled porosity of sewage sludge/soil mixture (unitless)
\bar{H}	=	nondimensional Henry's Law constant for the pollutant
θ_a	=	air-filled porosity of sewage sludge/soil mixture (unitless)
d_f	=	depth of a monofill cell (m)

In this equation, the non-dimensional Henry's Law constant is calculated as:

$$\begin{aligned}
 \dot{H} &= \frac{H(\text{atm}\cdot\text{m}^3/\text{mol})}{R(\text{atm}\cdot\text{m}^3/\text{mol}\cdot^\circ\text{K}) T(^\circ\text{K})} \\
 &= \frac{(0.0054)}{(8.21 \times 10^{-5})(288)} \\
 &= 0.23
 \end{aligned}
 \tag{35}$$

where:

\dot{H} = nondimensional Henry's Law constant for the pollutant
 H = Henry's Law constant for the pollutant ($\text{atm}\cdot\text{m}^3/\text{mol}$)
 R = ideal gas constant ($8.21 \times 10^{-5} \text{ m}^3\cdot\text{atm}/\text{mol}\cdot\text{K}$)
 T = temperature (K)

5.3.4.1.2 Pollutant Losses Through Volatilization

It is assumed that each monofill cell receives deposits of sewage sludge on each of three consecutive days. Each deposit is uncovered for a total of four hours before application of a daily cover of soil. The time that an individual cell is uncovered (in years) is then:

$$\begin{aligned}
 t_{un} &= \frac{(4 + 4 + 4)(\text{hr})}{8.776 \times 10^3(\text{hr/yr})} \\
 &= 1.4 \times 10^{-3}(\text{yr})
 \end{aligned}
 \tag{36}$$

where:

t_{un} = time that each individual monofill cell contains uncovered sewage sludge (yr)

The fraction of the facility's active lifetime that a typical cell will be uncovered is calculated as:

$$\begin{aligned}
 f_{un} &= \frac{t_{un}(yr)}{LF(yr)} \\
 &= \frac{(1.4 \times 10^{-3})}{(20)} \\
 &= 6.8 \times 10^{-5}
 \end{aligned}
 \tag{37}$$

where:

f_{un} = fraction of facility's active lifetime that a typical cell contains sewage sludge without soil cover (unitless)
 t_{un} = time that each individual monofill cell contains uncovered sewage sludge (yr)
 LF = active lifetime of monofill (yr)

The average monofill cell is assumed to contain sewage sludge for half the active lifetime of the facility. The fraction of the facility's active lifetime that such a cell contains sewage sludge protected by temporary cover is:

$$\begin{aligned}
 f_{co} &= \frac{1}{2} - f_{un} \\
 &= \frac{1}{2} - 6.8 \times 10^{-5} \\
 &= 0.49993
 \end{aligned}
 \tag{38}$$

where:

f_{co} = fraction of facility's active lifetime that typical cell contains sewage sludge with temporary soil cover (unitless)
 f_{un} = fraction of facility's active lifetime that a typical cell contains sewage sludge without soil cover (unitless)

Equations 7 and 8 (reproduced in these sample calculations as equations 40 and 41) are based on the concentration of pollutant in air-filled pore space within the monofill. This concentration can be related to the total concentration of pollutant in sewage sludge/soil (arbitrarily set to 1 kg/m³) as:

$$\begin{aligned}
 C_a &= \frac{C_t (\text{kg/m}^3)}{\frac{BD (\text{kg/m}^3) KD (\text{m}^3/\text{kg})}{\dot{H}} + \frac{\theta_w}{\dot{H}} + \theta_a} \\
 &= \frac{(1)}{\frac{(1400)(0.033)}{(0.23)} + \frac{(0.2)}{(0.23)} + (0.2)} \\
 &= 0.0050 (\text{kg/m}^3)
 \end{aligned} \tag{39}$$

where:

- C_a = vapor concentration of pollutant in air-filled pore space of treated soil (kg/m^3)
- C_t = total concentration of pollutant in sewage sludge/soil mixture (kg/m^3)
- BD = bulk density of sewage sludge/soil mixture (kg/m^3)
- KD = equilibrium partition coefficient for the pollutant (m^3/kg)
- \dot{H} = nondimensional Henry's Law constant for the pollutant
- θ_w = water-filled porosity of sewage sludge/soil mixture (unitless)
- θ_a = air-filled porosity of sewage sludge/soil mixture (unitless)

Emissions from an uncovered landfill cell are described by:

$$\begin{aligned}
 q_{un} &= \frac{0.17 \omega (\text{m/sec}) (0.994)^{[T(\text{K})-293]} C_a (\text{kg/m}^3)}{\sqrt{MW}} \\
 &= \frac{0.17 (4.5) (0.994)^{(288-293)} (0.0050)}{\sqrt{78.1}} \\
 &= 4.4 \times 10^{-4} (\text{kg/m}^2 \cdot \text{sec})
 \end{aligned} \tag{40}$$

where:

- q_{un} = emission rate from treated soil during uncovered period ($\text{kg/m}^2 \cdot \text{sec}$)
- 0.17 = empirical constant transferred from literature source of equation
- ω = wind speed (m/sec)
- 0.994 = empirical constant transferred from literature source of equation
- T = temperature (K)
- 293 = 15°C (converted to K)
- C_a = concentration of pollutant in air-filled pore space of sewage sludge/soil mixture (kg/m^3)
- MW = molecular weight of pollutant (g/mole)

For a cell with soil cover:

$$\begin{aligned}
 q_{co} &= \frac{9.2 \times 10^{-5} \theta_{ca}^{(10/3)} 1.006^{[T(^{\circ}K) - 293]} C_s (\text{kg/m}^3)}{\sqrt{MW} d_c (\text{m}) \theta_{ca}^2} \\
 &= \frac{9.2 \times 10^{-5} (0.2)^{(10/3)} 1.006^{(288-293)} (0.0050)}{\sqrt{(78.1)} (0.3) (0.4)^2} \\
 &= 4.9 \times 10^{-9} (\text{kg/m}^2 \cdot \text{sec})
 \end{aligned} \tag{41}$$

where:

q_{co}	=	emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
9.2×10^{-5}	=	empirical constant transferred from literature source of equation
θ_{ca}	=	air-filled porosity of cover layer (unitless)
1.006	=	empirical constant transferred from literature source of equation
C_s	=	concentration of pollutant in air-filled pore space of sewage sludge/soil mixture (kg/m^3)
MW	=	molecular weight of pollutant (g/mole)
d_c	=	depth of cover (m)
θ_{ca}	=	total porosity of cover layer (unitless)

Estimated emissions from uncovered and temporarily covered monofill cells are combined to derive a time-weighted average rate of emissions from a monofill cell during the facility's active lifetime:

$$\begin{aligned}
 q_{ac} &= q_{un} (\text{kg/m}^2 \cdot \text{sec}) f_{un} + q_{co} (\text{kg/m}^2 \cdot \text{sec}) f_{co} \\
 &= (4.4 \times 10^{-4}) (6.8 \times 10^{-5}) + (4.9 \times 10^{-9}) (0.50) \\
 &= 3.3 \times 10^{-8} (\text{kg/m}^2 \cdot \text{sec})
 \end{aligned} \tag{42}$$

where:

q_{ac}	=	time-weighted average rate of emissions from typical landfill cell over the active lifetime of the monofill ($\text{kg/m}^2 \cdot \text{sec}$)
q_{un}	=	rate of pollutant volatilization from an uncovered monofill cell ($\text{g/m}^2 \cdot \text{sec}$)
f_{un}	=	fraction of monofill's active lifetime that typical cell contains uncovered sewage sludge (unitless)
q_{co}	=	emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
f_{co}	=	fraction of facility's active lifetime that typical cell contains sewage sludge and temporary soil cover (unitless)

The estimated loss rate is converted to a first-order loss coefficient as:

$$\begin{aligned}
 K_{va} &= \frac{q_{ac} (\text{kg/m}^3 \cdot \text{sec}) \cdot 3.16 \times 10^7}{d_f (\text{m}) C_t} \\
 &= \frac{(3.3 \times 10^{-8}) \cdot 3.16 \times 10^7}{(3.46)(1)} \\
 &= 0.300 (\text{yr}^{-1})
 \end{aligned}
 \tag{43}$$

where:

K_{va}	=	first-order loss rate coefficient for volatilization during facility's active operation (yr^{-1})
q_{ac}	=	time-weighted average rate of pollutant volatilization from a monofill ($\text{g/m}^2 \cdot \text{sec}$)
3.16×10^7	=	conversion factor (sec^{-1}) (yr^{-1})
d_f	=	depth of a monofill cell (m)
C_t	=	total concentration of pollutant in sewage sludge/soil mixture (assumed to be 1 kg/m^3)

Estimated coefficients for losses to volatilization and leaching are combined with an assumed rate of degradation to yield a "lumped" coefficient describing the total rate of pollutant loss through all three pathways during the facility's active lifetime:

$$\begin{aligned}
 K_{ta} &= K_{lec} (\text{yr}^{-1}) + K_{va} (\text{yr}^{-1}) + K_{deg} (\text{yr}^{-1}) \\
 &= (0.0031) + (0.300) + (0) \\
 &= 0.303 (\text{yr}^{-1})
 \end{aligned}
 \tag{44}$$

where:

K_{ta}	=	coefficient for total rate of pollutant loss through leaching, volatilization, and degradation during facility's active operation (yr^{-1})
K_{lec}	=	rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
K_{va}	=	rate coefficient for loss of pollutant to volatilization from active monofill (yr^{-1})
K_{deg}	=	degradation rate coefficient for monofill (yr^{-1})

The fraction of total pollutant loss attributable to each individual process during the facility's active phase is then:

$$f_{la} = \frac{K_{lec}(yr^{-1})}{K_{ta}(yr^{-1})} = \frac{(0.0031)}{(0.303)} = 0.01$$

$$f_{va} = \frac{K_{va}(yr^{-1})}{K_{ta}(yr^{-1})} = \frac{(0.300)}{(0.303)} = 0.99 \quad (45)$$

$$f_{da} = \frac{K_{deg}(yr^{-1})}{K_{ta}(yr^{-1})} = \frac{(0)}{(0.303)} = 0$$

where:

- f_{la} = fraction of total pollutant loss during facility's active operation attributable to leaching (unitless)
- K_{lec} = rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
- K_{ta} = rate coefficient for total loss of pollutant during monofill's active lifetime (yr^{-1})
- f_{va} = fraction of total pollutant loss during facility's active operation attributable to volatilization (unitless)
- K_{va} = rate coefficient for loss of pollutant to volatilization from active monofill (yr^{-1})
- f_{da} = fraction of total pollutant loss during facility's active operation attributable to degradation (unitless)
- K_{deg} = degradation rate coefficient for monofill (yr^{-1})

The fraction of total pollutant loading lost during the facility's active lifetime is calculated as follows:

$$\begin{aligned} f_{sc} &= 1 - \frac{M_{LF}}{LF} \\ &= 1 - \frac{(2.8)}{(20)} \\ &= 0.86 \end{aligned} \quad (46)$$

where:

- f_{sc} = fraction of total pollutant lost during facility's active lifetime (unitless)
- M_{LF} = mass of pollutant in soil at end of monofill's active lifetime of operation (kg/ha)
- LF = number of years sewage sludge is deposited in monofill (yr)

The variable M_{LF} is evaluated as follows:

$$\begin{aligned}
 M_t &= 0 & (t=0) \\
 M_t &= [M_{t-1} + 1] e^{-K_a} & (1 \leq t \leq LF) \\
 &= [M_{t-1} + 1] e^{-(0.30)} & (1 \leq t \leq 20)
 \end{aligned}
 \tag{47}$$

where:

M_t = mass of pollutant in soil at end of year t (kg/ha)
 K_a = coefficient for total rate of pollutant loss during monofill's active lifetime of operation (yr^{-1})
 LF = active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)

to yield:

$$M_{LF} = M_{20} = 2.8 \tag{48}$$

where:

M_{LF} = mass of pollutant in soil at end of monofill's active lifetime of operation (kg/ha)

Thus, Equation 46 shows that about 86 percent of the mass of benzene in sewage sludge disposed of in the monofill is expected to be lost during the 20 years the facility receives sewage sludge.

Upon closure of the monofill, a permanent soil cover one meter deep is applied. The emission rate after closure is therefore reduced as follows:

$$\begin{aligned}
 q_{\infty} &= \frac{9.2 \times 10^{-5} \theta_a^{(10/3)} 1.006^{[T(^{\circ}\text{K}) - 293]} C_s (\text{g/m}^3)}{\sqrt{MW} d_c (\text{m}) \theta_a^2} \\
 &= \frac{9.2 \times 10^{-5} (0.2)^{(10/3)} 1.006^{(288 - 293)} (0.0050)}{\sqrt{(78.1)} (1) (0.4)^2} \\
 &= 1.5 \times 10^{-9} (\text{kg/m}^2 \cdot \text{sec})
 \end{aligned}
 \tag{49}$$

where:

q_{∞} = emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
 9.2×10^{-5} = empirical constant transferred from literature source of equation
 θ_a = air-filled porosity of cover layer (unitless)
 1.006 = empirical constant transferred from literature source of equation
 T = temperature (K)
 293 = 15°C (converted to K)

C_a	=	concentration of pollutant in air-filled pore space of sewage sludge/soil mixture (kg/m^3)
MW	=	molecular weight of pollutant (g/mole)
d_c	=	depth of cover (m)
θ_{ca}	=	total porosity of cover layer (unitless)

This rate of emissions is converted to a first-order loss coefficient as:

$$\begin{aligned}
 K_{vi} &= \frac{q_{\infty}(\text{kg/m}^2 \cdot \text{sec}) 3.16 \times 10^7}{d_f} \\
 &= \frac{(1.5 \times 10^{-9}) 3.16 \times 10^7}{(3.46)} \\
 &= 0.013 (\text{yr}^{-1})
 \end{aligned} \tag{50}$$

where:

K_{vi}	=	rate coefficient for loss of pollutant to volatilization from inactive monofill (yr^{-1})
q_{∞}	=	emission rate from treated soil for covered period ($\text{kg/m}^2 \cdot \text{sec}$)
3.16×10^7	=	conversion factor (sec^{-1}) (yr^{-1}) ⁻¹
d_f	=	depth of a monofill cell (m)

Rate coefficients for losses to leaching and degradation are assumed to be unaffected by soil cover. The lumped rate of loss for the inactive monofill is therefore described by:

$$\begin{aligned}
 K_u &= K_{lec} (\text{yr}^{-1}) + K_{vi} (\text{yr}^{-1}) + K_{deg} (\text{yr}^{-1}) \\
 &= (0.0031) + (0.013) + (0) \\
 &= 0.017 (\text{yr}^{-1})
 \end{aligned} \tag{51}$$

where:

K_u	=	coefficient for total rate of pollutant loss from inactive monofill (yr^{-1})
K_{lec}	=	rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
K_{vi}	=	coefficient for rate of pollutant loss through volatilization from inactive monofill (yr^{-1})
K_{deg}	=	degradation rate coefficient for monofill (yr^{-1})

The fraction of loss from an inactive monofill attributable to each individual process is calculated as:

$$\begin{aligned}
 f_{li} &= \frac{K_{lec}(yr^{-1})}{K_u(yr^{-1})} = \frac{(0.0031)}{(0.016)} = 0.19 \\
 f_{vi} &= \frac{K_{vi}(yr^{-1})}{K_u(yr^{-1})} = \frac{(0.013)}{(0.016)} = 0.81 \\
 f_{di} &= \frac{K_{deg}(yr^{-1})}{K_u(yr^{-1})} = \frac{(0)}{(0.016)} = 0
 \end{aligned}
 \tag{52}$$

where:

f_{li}	=	fraction of total pollutant loss from inactive monofill attributable to leaching (unitless)
K_{lec}	=	rate coefficient for loss of pollutant to leaching from monofill (yr^{-1})
K_u	=	coefficient for total rate of pollutant loss from inactive monofill (yr^{-1})
f_{vi}	=	fraction of total pollutant loss from inactive monofill attributable to volatilization (unitless)
K_{vi}	=	coefficient for rate of pollutant loss through volatilization from inactive monofill (yr^{-1})
f_{di}	=	fraction of total pollutant loss from inactive monofill attributable to degradation (unitless)
K_{deg}	=	degradation rate coefficient for monofill (yr^{-1})

5.3.4.2 Pollutant Criteria Calculations for Ground-Water Pathway

Derivation of criteria for the ground-water pathway begins with the calculation of an adjusted reference water concentration. For benzene, this value is calculated from the pollutant level by subtracting an estimated background concentration of the pollutant in ground water (assumed to be zero):

$$\begin{aligned}
 RC_{gw} &= MCL(mg/l) - C_b(mg/l) \\
 &= (0.005) - (0) \\
 &= 0.005(mg/l)
 \end{aligned}
 \tag{53}$$

where:

RC_{gw}	=	reference concentration for pollutant in ground water (mg/l)
MCL	=	maximum pollutant level for drinking water (mg/l)
C_b	=	average background concentration of pollutant in drinking water from wells (mg/l)

The next step is to use the adjusted reference water concentration of pollutant in well water to calculate a reference concentration of pollutant in leachate beneath the facility. The maximum rate of pollutant loss for a monofill (kg/yr) will occur in the year immediately following the last deposit of sewage sludge, since the total mass of pollutant at the site reaches its peak at that time. For benzene, this peak rate of loss could be maintained for a maximum length of time described by:

$$\begin{aligned} TP &= \frac{LF(yr)}{1 - e^{[-K_a(yr^{-1})LF(yr)]}} \\ &= \frac{(20)}{1 - e^{-(0.30)(20)}} \\ &= 20.05(yr) \end{aligned} \tag{54}$$

where:

TP = length of square wave in which maximum total loss rate of pollutant depletes total mass of pollutant applied to site (yr)
 LF = active lifetime of monofill (yr)
 K_a = rate coefficient for total loss of pollutant during monofill's active lifetime (yr⁻¹)

This result is used to prepare inputs for VADOFT, which when linked with AT123D predict the maximum concentration in ground water at a selected receptor location. For benzene, the ratio of this concentration to the concentration in leachate is:

$$\begin{aligned} f_{wel} &= \frac{C_{wel}(mg/l)}{C_{lec}(mg/l)} \\ &= \frac{(0.31)}{(1)} \\ &= 0.31 \end{aligned} \tag{55}$$

where:

f_{wel} = ratio of predicted concentration in well to concentration in leachate (unitless)
 C_{wel} = predicted concentration of the pollutant in well (mg/l)
 C_{lec} = unit concentration of the pollutant in leachate (1 mg/l)

This ratio is used to back-calculate a reference concentration of pollutant in leachate:

$$\begin{aligned}
 RC_{lec} &= \frac{RC_{gw}(\text{mg/l})}{f_{wel}} \\
 &= \frac{(0.005)}{(0.31)} \\
 &= 0.016(\text{mg/l})
 \end{aligned}
 \tag{56}$$

where:

RC_{lec} = reference concentration of pollutant in water leaching from the monofill (mg/l)
 RC_{gw} = reference concentration for pollutant in ground water (kg/m³)
 f_{wel} = ratio of pollutant concentration in well-water to concentration in leachate beneath the surface disposal facility (unitless)

Next, multiplying this reference concentration (in mg/l) by the assumed net recharge (in m/yr) and adjusting units yields, the reference flux of pollutant mass from the site can be calculated:

$$\begin{aligned}
 RF_{gw} &= 10 RC_{lec}(\text{mg/l}) NR(\text{m/yr}) \\
 &= 10 (0.016)(0.5) \\
 &= 0.08(\text{kg/ha} \cdot \text{yr})
 \end{aligned}
 \tag{57}$$

where:

RF_{gw} = reference annual flux of pollutant beneath the site (kg/ha·yr)
 10 = conversion factor ([mg·m]/l) (kg/ha)⁻¹
 RC_{lec} = reference concentration for pollutant in leachate from sewage sludge monofill (kg/m³)
 NR = net recharge (m/yr)

The mass of solids contained in 1 m³ of pure sewage sludge is calculated as:

$$\begin{aligned}
 MS &= \frac{f_{sol} \rho_{sl} \rho_w}{f_{sol} \rho_w + (1-f_{sol}) \rho_{sl}} \\
 &= \frac{(0.2)(1200)(1000)}{(0.2)(1000) + (1-0.2)(1200)} \\
 &= 210(\text{kg/m}^3)
 \end{aligned}
 \tag{58}$$

where:

MS	=	mass of solids in one m ³ of pure sewage sludge (kg/m ³)
f _{sol}	=	fraction of solids in sewage sludge (by mass, kg/kg)
ρ _{sl}	=	particle density of sewage sludge (kg/m ³)
ρ _w	=	density of water (kg/m ³)

The mass of sewage sludge in one hectare of landfill is:

$$\begin{aligned}
 SC &= d_f f_{sl} MS 10^4 \\
 &= (3.46)(0.64)(210) 10^4 \\
 &= 4.6 \times 10^6 \text{ (kg/ha)}
 \end{aligned} \tag{59}$$

where:

SC	=	estimated mass of sewage sludge contained in one hectare of completed monofill (kg/ha)
d _f	=	depth of a monofill cell (m)
f _{sl}	=	fraction of monofill's volume containing sewage sludge (unitless)
MS	=	mass of solids in one m ³ of pure sewage sludge (kg/m ³)
10 ⁴	=	conversion factor (1/m ²) (1/ha) ⁻¹

The reference flux is converted to an equivalent concentration in sewage sludge by:

$$\begin{aligned}
 RCS &= \frac{TP(yr) RF_{gw}(\text{kg/ha} \cdot \text{yr}) 10^6}{f_{le} SC(\text{kg/ha})} \\
 &= \frac{(20.0)(0.08) 10^6}{(0.01)(4.6 \times 10^6)} \\
 &= 34 \text{ (mg/kg)}
 \end{aligned} \tag{60}$$

where:

RCS	=	reference dry-weight concentration of pollutant in sewage sludge (mg/kg)
TP	=	length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant at site (sec or yr)
RF _{gw}	=	reference annual flux of pollutant to the unsaturated soil zone beneath the surface disposal facility (kg/ha · yr)
10 ⁶	=	conversion factor (kg) (mg) ⁻¹
f _{le}	=	fraction of pollutant loss during monofill's active lifetime that is lost to leaching (unitless)
SC	=	mass of sewage sludge contained in one hectare of surface disposal facility (kg/ha)

5.3.4.3 Pollutant Criteria Calculations for Vapor Pathway

Calculation of numerical criteria for the vapor pathway begins with the derivation of a reference air concentration for benzene:

$$\begin{aligned} RC_{air} &= \frac{RL \text{ BW(kg)} 1000}{I_a (\text{m}^3/\text{day}) q_1^* (\text{mg/kg} \cdot \text{day})} \\ &= \frac{(10^{-4})(70) 1000}{(20)(0.029)} \\ &= 12 (\mu\text{g}/\text{m}^3) \end{aligned} \quad (61)$$

where:

RC_{air}	=	reference air concentration for pollutant ($\mu\text{g}/\text{m}^3$)
RL	=	risk level (incremental risk of cancer per lifetime)
BW	=	body weight (kg)
I_a	=	inhalation volume (m^3/day)
q_1^*	=	human cancer potency ($\text{kg} \cdot \text{day} \cdot \text{mg}$)
1000	=	conversion factor (mg) (μg) ⁻¹

The next step is to relate releases of volatilized benzene to the expected concentration in ambient air, based on a source-receptor ratio calculated to relate the concentration of pollutant in ambient air at the HEI's location to the rate that pollutant is emitted from the facility. The appropriate value for the standard deviation of the vertical distribution of pollutant concentration is calculated as:

$$x = 0.001 r' (\text{m}) = 0.001(50) = 0.05 (\text{km}) \quad (62)$$

where:

x	=	intermediate variable for Equation 63
r'	=	distance from the monofill center to the receptor (m)

and:

$$\sigma_z = a x^b = 15.209(0.05)^{(0.81558)} = 1.3 (\text{km}) \quad (63)$$

where:

σ_z	=	standard deviation of the vertical concentration distribution (m)
a,b	=	empirical constants
x	=	intermediate variable

The vertical term v is a function of source height, the mixing layer height, and σ_z . Under stable conditions the mixing layer height is assumed infinite and for a pollutant release height of zero, v equals one. The lateral virtual distance is the distance from a virtual point source to the monofill, such that the angle θ subtended by the monofill's width, is 22.5° . This distance is calculated as:

$$\begin{aligned} x_y &= \sqrt{\frac{A(m^2)}{\pi}} \cot\left(\frac{\theta}{2}\right) \\ &= \sqrt{\frac{10,000}{3.14}} \cot\left(\frac{22.5}{2}\right) \\ &= 284(m) \end{aligned} \tag{64}$$

where:

x_y = lateral virtual distance to receptor location (m)
 A = surface area of surface disposal facility (m^2)
 θ = angle subtended by width of disposal site at distance equal to estimated virtual distance from site (degrees)

The source-receptor ratio is calculated as:

$$\begin{aligned} SRR &= 2.032 \frac{A(m^2) \omega(m/sec)}{[r'(m) + x_y(m)] \omega \sigma_z(m)} \\ &= 2.032 \frac{(10,000)(1)}{[(50) + (284)](4.5)(1.3)} \\ &= 10(sec/m) \end{aligned} \tag{65}$$

where:

SRR = source-receptor ratio (sec/m)
 2.032 = empirical constant transferred from literature source of equation
 A = area of monofill (m^2)
 v = vertical term (unitless)
 r' = distance from the monofill center to the receptor (m)
 x_y = lateral virtual distance (m)
 ω = wind speed (m/sec)
 σ_z = standard deviation of the vertical concentration distribution (m)

The source-receptor ratio is combined with the reference air concentration to calculate a reference annual flux of pollutant:

$$\begin{aligned}
 RF_{air} &= \frac{316 RC_{air} (\mu g/m^3)}{SRR (sec/m)} \\
 &= \frac{316(12)}{(10)} \\
 &= 370 (kg/ha \cdot yr)
 \end{aligned}
 \tag{66}$$

where:

$$\begin{aligned}
 RF_{air} &= \text{reference annual flux of pollutant emitted from the site (kg/ha} \cdot \text{yr)} \\
 316 &= \text{conversion factor } (\mu g/m^2 \cdot \text{sec}) (kg/ha \cdot \text{yr})^{-1} \\
 RC_{air} &= \text{reference air concentration for pollutant } (\mu g/m^3) \\
 SRR &= \text{source-receptor ratio (sec/m)}
 \end{aligned}$$

The reference annual flux of pollutant is calculated by considering the maximum fraction of total pollutant mass expected to be lost during the equivalent of a human lifetime, as well as the fraction of that loss attributable to volatilization:

$$\begin{aligned}
 f_{vls} &= f_{va} f_{ac} + f_{vi} (1 - f_{ac}) [1 - e^{-K_i(LS-LF)}] \\
 &= (0.99)(0.86) + (0.81)(1 - 0.85) [1 - e^{-(0.017)(70-20)}] \\
 &= 0.91
 \end{aligned}
 \tag{67}$$

where:

$$\begin{aligned}
 f_{vls} &= \text{fraction of pollutant mass which volatilizes over a human lifetime (unitless)} \\
 f_{va} &= \text{fraction of pollutant loss during monofill's active lifetime that is lost to volatilization (unitless)} \\
 f_{ac} &= \text{fraction of total pollutant loading lost during active operation of monofill facility (unitless)} \\
 K_i &= \text{rate coefficient for total loss of pollutant from inactive monofill (yr}^{-1}\text{)} \\
 LS &= \text{lifespan of average individual (yr)} \\
 LF &= \text{active lifetime of monofill facility: the period in which the facility accepts sewage sludge (yr)}
 \end{aligned}$$

This result is combined with the reference annual flux of pollutant and the estimated mass of sewage sludge in one hectare of monofill (Equation 59) to calculate a reference concentration of pollutant in monofilled sewage sludge:

$$\begin{aligned}
 \text{RCS} &= \frac{\text{RF}_{\text{air}}(\text{kg/ha} \cdot \text{yr}) \text{LS}(\text{yr}) 10^6(\text{mg/kg})}{f_{\text{vk}} \text{SC}(\text{kg/ha})} \\
 &= \frac{(370)(70) 10^6}{(0.91)(4.6 \times 10^6)} \\
 &= 6100(\text{mg/kg})
 \end{aligned}
 \tag{68}$$

where:

RCS	=	reference concentration of pollutant in sewage sludge for volatilization pathway (mg/kg dry weight)
RF _{air}	=	reference annual flux of pollutant to air above the site (kg/ha • yr)
LS	=	lifespan of average individual (yr)
10 ⁶	=	conversion factor (kg) (mg) ⁻¹
f _{vk}	=	fraction of pollutant mass which volatilizes over a human lifetime (unitless)
SC	=	mass of sewage sludge contained in one hectare of surface disposal facility (kg/ha)

5.4 RISK ASSESSMENT METHODOLOGY FOR SURFACE IMPOUNDMENT PROTOTYPE

Algorithms for deriving pollutant criteria for sewage sludge placed in a prototype surface impoundment are based on methods described in U.S. EPA (1990a), to which the reader is referred for a more detailed discussion. The present methodology refines that earlier work with its inclusion of "mass balance" calculations to partition pollutant losses among competing loss processes within the impoundment.

5.4.1 Methodology for Mass Balance

Pollutants in sewage sludge are assumed to enter the surface impoundment facility through continuous inflow and to be removed through four general processes:

- 1) pollutant is lost to degradation within the unit (e.g., by photolysis, hydrolysis, or microbial decay),

- 2) pollutant is transported out of the unit by seeping through the floor of the impoundment,
- 3) pollutant is lost through outflow (possibly for return to the treatment works), and
- 4) pollutant volatilizes from the liquid surface of the impoundment.

A mathematical model for describing these four processes has been adapted from a two-layer model by Thomann and Mueller (1987) initially developed for modeling toxic substances in a lake. For the water column of a lake, those authors consider the inflow and outflow of pollutant, diffusive exchange between the sediment layer and the water column, degradation, volatilization, settling of particulate toxicant from the water column to the sediment, and re-suspension of particulate from the sediment layer to the water column. For the sediment layer, they consider diffusive exchange with the water column, decay processes, particulate settling from the overlying water column, re-suspension flux from the sediment because of water column, and loss of toxicant from the sediment due to net sedimentation or burial.

The methodology for deriving pollutant limits for sewage sludge uses a similar two-layer model. The "liquid" layer begins at the surface and has the same average solids content as inflow to the facility. The "sediment" layer beneath has a higher solids content. Although a gradient of solids concentrations is likely to form in an actual impoundment, the two-layer model assumes each layer is homogenous with respect to both solids and pollutant concentrations.

Thomann and Mueller provide explicit equations for predicting settling velocities for particulate and rates of diffusive exchange between the two layers. The present methodology derives simpler equations by making a number of simplifying assumptions: First, it is assumed that the sediment layer will eventually reach the surface of the impoundment. Second, it is assumed that outflow contains negligible concentrations of suspended solids. Third, all loss processes are approximated as proportional to pollutant concentration. In other words, the loss rate at any given time is assumed to be proportional to the pollutant concentration in the impoundment at that time. Fourth, concentrations of pollutant within each layer are assumed to have reached steady-state and to be partitioned at equilibrium between adsorbed and dissolved phases. And finally, rates of pollutant transfer and loss at the time that impoundment is half

filled with sediment are assumed to be typical of the facility both before and after it fills with sewage sludge solids.

If rates of loss to effluent, volatilization, seepage, and degradation are all proportional to pollutant concentration, the maximum total rate of loss will occur should equilibrium concentrations be attained. Moreover, after the continuous deposition of sewage sludge to the facility is terminated, the rates at which pollutant is lost to seepage and volatilization should decline. By assuming that equilibrium conditions are representative of the entire (active and inactive) lifetime of the surface impoundment facility prototype, this methodology probably overestimates rates of pollutant loss through seepage and volatilization, leading to conservative criteria for this prototype.

5.4.1.1 Pollutant Losses from Liquid Layer

The concentration of pollutant in the inflow of the impoundment (C_i) and in the liquid layer (C_l) are assumed to remain constant throughout the facility's active lifetime. The partitioning of pollutant in the liquid layer is described as:

$$Q_i C_i = Q_o f_{dl} C_l + K_{degl} A d_l C_l + K_{vol} f_{dl} A C_l + Q_{loc} f_{dl} A C_l + DVC_l \quad (69)$$

where:

Q_i	=	rate at which sewage sludge enters the impoundment (m ³ /sec)
C_i	=	concentration of pollutant in inflow to the impoundment (kg/m ³)
Q_o	=	rate at which outflow leaves the impoundment (m ³ /sec)
f_{dl}	=	fraction of total pollutant in liquid layer that is dissolved (unitless)
C_l	=	total concentration of pollutant (adsorbed and dissolved) in liquid layer (kg/m ³)
K_{degl}	=	rate of pollutant degradation in liquid layer (sec ⁻¹)
A	=	surface area of impoundment (m ²)
d_l	=	depth of liquid layer (m)
K_{vol}	=	rate of pollutant volatilization from liquid layer (m/sec)
Q_{loc}	=	rate of seepage beneath the impoundment (m/sec)
DV	=	rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m ³ /sec)

Because the total depth of the impoundment (including both liquid and sediment layers) is assumed constant, the depth of the liquid layer is reduced as more sewage sludge accumulates in

the sediment layer. If the rate at which the sediment accumulates is constant over the active lifetime of the facility, the rate of accumulation can be determined by dividing the total volume of the impoundment by its expected active lifetime:

$$DV = \frac{d_{\text{tot}} A}{TF} \quad (70)$$

where:

DV	=	rate at which sediment accumulates (m ³ /sec)
d _{tot}	=	total depth of impoundment (m)
A	=	surface area of impoundment (m ²)
TF	=	estimated active lifetime of facility (sec)

The active lifetime of the facility is calculated as:

$$TF = \frac{d_{\text{tot}} A S_2}{Q_i S_1} \quad (71)$$

where:

TF	=	estimated active lifetime of facility (sec)
d _{tot}	=	total depth of impoundment (m)
A	=	surface area of impoundment (m ²)
S ₂	=	concentration of solids in sediment layer (kg/m ³)
Q _i	=	rate at which sewage sludge enters the impoundment (m ³ /sec)
S ₁	=	concentration of solids in liquid layer (kg/m ³)

For the first term on the right of Equation 69 $[Q_o f_{d1} C_1]$, the volume of outflow from the facility (Q_o) is calculated to be consistent with assumptions about rates of inflow, seepage, and accumulation of the sediment layer as follows:

$$Q_o = Q_i \left(1 - \frac{S_1}{\rho_{sl}} \right) - Q_{\text{sep}} A - DV \left(1 - \frac{S_2}{\rho_{sl}} \right) \quad (72)$$

where:

Q _o	=	rate at which outflow leaves the impoundment (m ³ /sec)
Q _i	=	rate at which sewage sludge enters the impoundment (m ³ /sec)
S ₁	=	concentration of solids in liquid layer (kg/m ³)
ρ _{sl}	=	particle density of sewage sludge (kg/m ³)
Q _{sep}	=	seepage rate for both liquid and sediment layers (m/sec)
A	=	surface area of impoundment (m ²)
DV	=	rate at which sediment accumulates (m ³ /sec)
S ₂	=	concentration of solids in sediment layer (kg/m ³)

The concentration of solids in the liquid and sediment layers is calculated from parameters describing the percent solids (by mass) in each layer:

$$S_1 = \frac{\rho_{sl} \rho_w P_1}{\rho_w P_1 + (1-P_1) \rho_{sl}}$$

$$S_2 = \frac{\rho_{sl} \rho_w P_2}{\rho_w P_1 + (1-P_2) \rho_{sl}}$$
(73)

where:

S_1	=	concentration of solids in liquid layer (kg/m ³)
ρ_{sl}	=	particle density of sewage sludge (kg/m ³)
ρ_w	=	density of water (kg/m ³)
P_1	=	percent solids (by mass) in liquid layer (kg/kg)
S_2	=	concentration of solids in sediment layer (kg/m ³)
P_2	=	percent solids (by mass) in sediment layer (kg/kg)

In each layer pollutant is partitioned between adsorbed and dissolved phases. As discussed earlier, the partitioning depends on both the pollutant-specific partition coefficient and the concentration of solids in the layer:

$$f_{dl} = \frac{1}{1 + KD S_1}$$

$$f_{pl} = 1 - f_{dl}$$
(74)

where:

f_{dl}	=	fraction of pollutant dissolved in the liquid layer
KD	=	pollutant-specific partition coefficient (m ³ /kg)
S_1	=	concentration of solids in liquid layer (kg/m ³)
f_{pl}	=	fraction of pollutant in liquid layer of surface impoundment adhering to solid particles (unitless)

The second term on the right side of Equation 69 [$K_{deg} Ad_1 C_1$] describes the rate of degradation of the pollutant in the liquid layer (through photolysis, hydrolysis, microbial decay, and other processes). Values for K_{deg} are taken from studies of anaerobic microbial degradation and are applied to pollutant in both dissolved and adsorbed phases.

The third term on the right side of Equation 69 [$K_{vol} f_{dl} AC_1$] describes pollutant loss from the liquid layer through volatilization. This term is the only part of Equation 69 that is directly

linked with human exposure. The overall mass transfer coefficient for volatilization (K_{vol}) is calculated with a two-film resistance model (Thomann and Mueller, 1987) in which the overall resistance equals the sum of the liquid and gas phase resistances:

$$\frac{1}{K_{vol}} = \frac{1}{K_l} + \frac{RT}{HK_g} \quad (75)$$

where:

K_{vol}	=	overall mass transfer coefficient for volatilization (m/sec)
K_l	=	mass transfer coefficient for the liquid later (m/sec)
R	=	ideal gas constant (8.21×10^{-5} atm·m ³ /K·mol)
T	=	temperature (K)
H	=	Henry's Law constant for pollutant (atm·m ³ /mol)
K_g	=	mass transfer coefficient for gas layer (m/sec)

Numerous methods for calculating K_l and K_g for water surfaces have been proposed (see, e.g., Hwang, 1982; Hwang and Thibodeaux, 1982; MacKay and Leinonen, 1975; MacKay and Yeun, 1983; Shen, 1982; Springer et al., 1984; U.S. EPA, 1987a; U.S. EPA, 1989c). This methodology follows an approach described in U.S. EPA (1987a, 1989c) for estimating volatilization from surface impoundments. The selection of appropriate equations for calculating mass transfer coefficients depends on two characteristics of the site: (1) the ratio of the impoundment's effective diameter (or "fetch") to its depth and (2) the local average wind speed. Effective diameter (in meters) is defined as the diameter of a circle with area equal to that of the impoundment. Depth is defined as that of the liquid layer. For the purpose of this calculation it is assumed to average half of the impoundment's total depth. The ratio of fetch to depth is therefore calculated as:

$$d_e = 2\sqrt{A/\pi}$$

$$FD = \frac{d_e}{d_l} \quad (76)$$

where:

d_e	=	effective diameter (or fetch) of site (m)
A	=	surface area of impoundment (m ²)
FD	=	ratio of fetch to depth (unitless)
d_l	=	depth of liquid layer (m)

For facilities where the average wind speed 10 m above the liquid surface is greater than 3.25 m/sec and $FD \geq 51.2$ (as in the scenario used for the surface impoundment prototype):

$$K_1 = 2.611 \times 10^{-7} U_{10}^2 \left(\frac{D_{cw}}{D_{eth}} \right)^{2/3} \quad (77)$$

where:

K_1	=	mass transfer coefficient for the liquid layer (m/sec)
U_{10}	=	average wind speed 10 m above surface (m/sec)
D_{cw}	=	diffusivity of pollutant in water (cm ² /sec)
D_{eth}	=	diffusivity of diethyl ether in water (cm ² /sec)

Calculation of the mass transfer coefficient for the gas phase is based on Hwang (1985). For all values of FD and U_{10} , K_g (m/sec) is calculated from:

$$K_g = 1.8 \times 10^{-3} U_{10}^{0.78} Sc_g^{-0.67} de^{-0.11} \quad (78)$$

where:

K_g	=	mass transfer coefficient for gas layer (m/sec)
U_{10}	=	average wind speed 10 m above surface (m/sec)
Sc_g	=	Schmidt number on gas side (unitless)

where Sc_g equals the Schmidt number on the gas side, defined as:

$$Sc_g = \frac{\mu_a}{\rho_a D_{ca}} \quad (79)$$

and where:

Sc_g	=	Schmidt number on gas side (unitless)
μ_a	=	viscosity of air (g/cm • sec)
ρ_a	=	density of air (g/cm ³)
D_{ca}	=	diffusivity of pollutant in air (cm ² /sec)

Equations 75 through 78 are sufficient to estimate K_{oll} , the overall mass transfer coefficient for the volatilization of the pollutant.

The fourth term on the right side of Equation 69 [$Q_{lec,d1}AC_1$] describes losses of dissolved pollutant (p. 5-49) from the liquid layer as a result of the seeping through the sediment layer and the floor of the impoundment. The rate of leachate (Q_{sep}) is based on measured values from sewage sludge lagoons. Only dissolved pollutant is included in this term. The fifth term of the

equation $[DVC_1]$ describes loss of adsorbed pollutants from the liquid layer as a result of the diminishing volume of that layer.

All terms on the right side of Equation 69 are proportional to the concentration of pollutant in the liquid layer. A coefficient for the total rate at which pollutant mass is lost from the liquid layer (K_{tot1} , in m^3/sec) can be defined as:

$$K_{tot1} = Q_o f_{d1} + K_{degl} d_1 A + K_{vol1} f_{d1} A + Q_{sep} f_{d1} A + DV \quad (80)$$

where:

K_{tot1}	=	lumped rate coefficient for pollutant loss from the liquid layer of surface impoundment (m^3/sec)
Q_o	=	rate at which outflow leaves the impoundment (m^3/sec)
f_{d1}	=	fraction of total pollutant in liquid layer that is dissolved (unitless)
K_{degl}	=	rate of pollutant degradation in liquid layer (sec^{-1})
d_1	=	depth of liquid layer (m)
A	=	surface area of impoundment (m^2)
K_{vol1}	=	rate of pollutant volatilization from liquid layer (m/sec)
Q_{sep}	=	rate of seepage beneath the impoundment (m/sec)
DV	=	rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

so that:

$$Q_i C_i = K_{tot1} C_1 \quad (81)$$

where:

Q_i	=	rate of inflow for sludge into a surface impoundment (m^3/sec)
C_i	=	concentration of pollutant in inflow to surface impoundment (kg/m^3)
K_{tot1}	=	lumped rate coefficient for pollutant loss from the liquid layer of surface impoundment (m^3/sec)
C_1	=	concentration of pollutant in liquid layer of surface impoundment (kg/m^3)

Because all estimated rates of pollutant loss from the liquid layer are proportional to the concentration of pollutants in this layer, total losses can be partitioned among competing loss processes according to fixed ratios. Of the total mass of pollutant lost from the liquid layer, the fraction lost to each process is:

$$f_{outl} = \frac{Q_o f_{dl}}{K_{totl}}$$

$$f_{degl} = \frac{K_{degl} d_{tot} A}{K_{totl}}$$

$$f_{voll} = \frac{K_{voll} f_{dl} A}{K_{totl}}$$

$$f_{sepl} = \frac{Q_{sep} f_{dl} A}{K_{totl}}$$

$$f_{dell} = \frac{DV}{K_{totl}}$$

(82)

where:

- f_{outl} = fraction of total pollutant lost from liquid layer that is lost in outflow from the impoundment (unitless)
- Q_o = rate at which outflow leaves the impoundment (m³/sec)
- f_{dl} = fraction of total pollutant in liquid layer that is dissolved (unitless)
- K_{totl} = lumped rate coefficient for pollutant loss from the liquid layer of surface impoundment (m³/sec)
- f_{degl} = fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
- K_{degl} = rate of pollutant degradation in liquid layer (sec⁻¹)
- A = surface area of impoundment (m²)
- f_{voll} = fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)
- f_{sepl} = fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
- Q_{sep} = rate of seepage beneath the impoundment (m/sec)
- f_{dell} = fraction of total pollutant lost from the liquid layer as a result of the diminishing volume of the liquid layer (unitless)
- DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m³/sec)

5.4.1.2 Pollutant Losses from Sediment Layer

Pollutant mass accumulates in the sediment layer as the depth of this layer increases eventually reaching the surface of the impoundment. If the only source of pollutant mass for the sediment layer is the losses estimated for the liquid layer:

$$Q_{sep} f_{d1} A C_1 + DV C_1 = K_{deg2} d_2 A C_2 + Q_{sep} f_{d2} A C_2 + DV C_2 \quad (83)$$

where:

Q_{sep}	=	seepage rate for both liquid and sediment layers (m/sec)
f_{d1}	=	fraction of pollutant in the liquid layer of surface impoundment that is dissolved (unitless)
A	=	surface area of surface disposal facility (m ²)
C_1	=	concentration of pollutant in liquid layer of surface impoundment (kg/m ³)
DV	=	rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m ³ /sec)
K_{deg2}	=	rate of pollutant degradation in sediment layer (sec ⁻¹)
d_2	=	depth of sediment layer (m)
C_2	=	total concentration of pollutant in sediment layer (kg/m ³)
f_{d2}	=	fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)

and:

$$f_{d2} = \frac{1}{1 + KD S_2} \quad (84)$$

where:

f_{d2}	=	fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)
KD	=	equilibrium partition coefficient for pollutant (m ³ /kg)
S_2	=	solids concentration in the sediment layer of a surface impoundment (kg/m ³)

A coefficient for the total loss or storage of pollutant in the sediment layer (K_{tot2} , m³/sec) can be defined as:

$$K_{tot2} = K_{deg2} d_2 A + Q_{sep} f_{d2} A + DV \quad (85)$$

where:

K_{tot2}	=	lumped rate coefficient for pollutant loss from the sediment layer of surface impoundment (m ³ /sec)
K_{deg2}	=	rate of pollutant degradation in sediment layer (sec ⁻¹)
d_2	=	depth of sediment layer (m)
A	=	surface area of surface disposal facility (m ²)
Q_{sep}	=	seepage rate for both liquid and sediment layers (m/sec)

- f_{d2} = fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)
 DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

As with the liquid layer, this coefficient can be partitioned into its individual components:

$$\begin{aligned}
 f_{deg2} &= \frac{K_{deg2} d_2 A}{K_{tot2}} \\
 f_{sep2} &= \frac{Q_{sep} f_{d2} A}{K_{tot2}} \\
 f_{del2} &= \frac{DV}{K_{tot2}}
 \end{aligned} \tag{86}$$

where:

- f_{deg2} = fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
 K_{deg2} = rate of pollutant degradation in sediment layer (sec^{-1})
 d_2 = depth of sediment layer (m)
 A = surface area of surface disposal facility (m^2)
 K_{tot2} = lumped rate coefficient for pollutant loss from the sediment layer of surface impoundment (m^3/sec)
 f_{sep2} = fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)
 Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)
 f_{d2} = fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)
 f_{del2} = fraction of pollutant reaching the sediment layer that is stored in the accumulating depth of this layer (unitless)
 DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

If concentrations of pollutant in the liquid and sediment layers can be approximated as steady-state for the duration of the impoundment's active lifetime, and if the partitioning of pollutant among competing loss processes halfway through the impoundment's active lifetime is assumed typical of its entire active phase, then the fraction of the yearly loading of pollutant lost during each year of the facility's active phase (f_{act}) can be calculated as:

$$f_{act} = f_{vol1} + f_{deg1} + f_{out1} + (f_{sep1} + f_{del1})(f_{deg2} + f_{sep2}) \tag{87}$$

where:

- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)

f_{vol1}	=	fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)
f_{deg1}	=	fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
f_{out1}	=	fraction of total pollutant lost from liquid layer that is lost in outflow from the impoundment (unitless)
f_{sep1}	=	fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
f_{del1}	=	fraction of pollutant loss from the liquid layer that is displaced by the accumulating sediment layer (unitless)
f_{deg2}	=	fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
f_{sep2}	=	fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)

Finally, if all pollutant is eventually lost from the impoundment and the partitioning of pollutant mass halfway through the facility's lifetime is generalized for the entire mass of pollutant, the fraction of pollutant mass lost through each pathway can be calculated as:

$$\begin{aligned}
 f_{sep} &= \frac{(f_{sep1} + f_{del1})f_{sep2}}{f_{act}} \\
 f_{vol} &= \frac{f_{vol1}}{f_{act}} \\
 f_{deg} &= \frac{f_{deg1} + (f_{sep1} + f_{del1})f_{deg2}}{f_{act}} \\
 f_{out} &= \frac{f_{deg1}}{f_{act}}
 \end{aligned}
 \tag{88}$$

where:

f_{sep}	=	fraction of total pollutant lost from the impoundment through seepage (unitless)
f_{sep1}	=	fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
f_{del1}	=	fraction of pollutant loss from the liquid layer that is displaced by the accumulating sediment layer (unitless)
f_{sep2}	=	fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)
f_{act}	=	fraction of pollutant lost during surface impoundment's active phase (unitless)
f_{vol}	=	fraction of total pollutant lost from the impoundment through volatilization (unitless)
f_{vol1}	=	fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)

f_{deg}	=	fraction of total pollutant lost from the impoundment through degradation (unitless)
f_{deg1}	=	fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
f_{deg2}	=	fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
f_{out}	=	fraction of total pollutant lost from the impoundment through outflow (unitless)

These results are used to calculate pollutant limits for the ground water and vapor pathways.

5.4.2 Methodology for the Ground-Water Pathway

Derivations of pollutant criteria for the ground-water pathway begin with the calculation of an adjusted reference water concentration (RC_{gw}) for each pollutant of concern. This value is calculated from the maximum pollutant level (MCL) by subtracting an estimated background concentration of the pollutant in ground water:

$$RC_{gw} = MCL - C_b \quad (89)$$

where:

RC_{gw}	=	adjusted reference water concentration (mg/l)
MCL	=	maximum pollutant level (mg/l)
C_b	=	average background concentration of pollutant in drinking water from wells (mg/l)

Alternatively, if no MCL is available, the reference water concentration is calculated for carcinogenic pollutants from a selected risk level and a human cancer potency:

$$RC_{gw} = \frac{RL \cdot BW}{q_i \cdot RE \cdot I_w} \quad (90)$$

where:

RC_{gw}	=	adjusted reference water concentration (mg/l)
RL	=	risk level (incremental risk of cancer per lifetime, unitless)
BW	=	human body weight (kg)
q_i	=	human cancer potency (mg/kg•day) ⁻¹ or (kg•day/mg)
RE	=	relative effectiveness of exposure through ingestion (unitless)
I_w	=	total water ingestion rate (l/day)

The next step is to use the reference concentration for the pollutant in well water to calculate a reference concentration of pollutant in leachate beneath the facility. As discussed in Section 5.3.2 for the monofill prototype, two mathematical models are combined to calculate an expected ratio between these two concentrations. The VADOFT component of the RUSTIC model (U.S. EPA, 1989a,b) estimates flow and transport through the unsaturated zone, and the AT123D model (Yeh, 1981) estimates pollutant transport through the saturated zone.

Minor adjustments have been made to the linked models to represent a phenomenon unique to this prototype: seepage from a surface impoundment can cause local elevation of the water table if rates of seepage exceed natural rates of aquifer recharge in the surrounding area. Such elevation, or mounding, of the water table has two implications for the expected concentrations of pollutants at a receptor well. The first is that the reduced vertical distance between the impoundment and the local water table will result in a shorter timespan for seepage from the impoundment to reach the saturated zone. The second is that an increased hydraulic gradient will form in the aquifer between the impoundment and the downgradient receptor well. This change in gradient will increase the expected rate of horizontal transport of the pollutant through the saturated zone.

To accommodate these two effects in the model calculations, this methodology modifies an approach used in the RUSTIC model. The first component of the model (VADOFT) performs calculations for a vertical column containing both unsaturated and saturated zones and predicts the extent to which the elevation of the water table will be increased by the flux of water seeping from the impoundment. Once the vertical column problem has been solved for mass and water fluxes at the water table elevation, the second model component (AT123D) simulates the movement of pollutants through the saturated zone, with adjustments to represent increased elevation of the water table. Unlike RUSTIC, however, the present methodology does not allow for partial feedback between the unsaturated and saturated zone components of the model; the saturated zone is represented separately by an analytical transport model.

The AT123D model accepts as input the flux of pure pollutant mass entering the top of the saturated zone and does not consider the extent of the pollutant's dilution by water from the source area or the impact of that water on ground-water flow within the saturated zone. When

the vertical movement of pollutant through the unsaturated zone is due only to natural recharge throughout the area, the gradient within the aquifer is a function of the water entering the saturated zone. Under these conditions, neglect of pollutant dilution in the source area may be valid. With a surface impoundment, however, neglect of the extent of the pollutant's initial dilution could result in nontrivial overestimation of the source concentration leading to overestimation of pollutant concentrations at the receptor well. Furthermore, neglect of mounding effects could lead to incorrect assumptions about the velocity of ground water flow near the site.

These concerns are addressed with three simple adjustments to the execution of the AT123D model. First, to correct for AT123D's potential overestimation of the original concentration of pollutant at the aquifer's boundary, the mass flux estimated from VADOFT results is adjusted by a dilution factor (D_f) as follows:

$$D_f = \frac{F_s}{(A Q_{sep} + F_s)} \quad (91)$$

where:

- | | | |
|-----------|---|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| D_f | = | dilution factor (unitless) |
| F_s | = | the volume of fluid passing through a vertical cross section of the aquifer oriented perpendicular to the direction of flow, and having a width equal to the source width and a depth equal to the saturated thickness of the aquifer (m^3/sec) |
| A | = | surface area of surface disposal facility (m^2) |
| Q_{sep} | = | seepage rate for both liquid and sediment layers (m/sec) |

In cases where seepage from the impoundment is not significant compared with the natural, regional rate of aquifer recharge, this dilution adjustment is inappropriate and can be left out of program execution.

The excess water released by seepage from a surface impoundment can also result in a superimposed radial velocity field on the background or regional velocity field of ground-water flow. In other words, the horizontal velocity of water within the aquifer can be slowed up-gradient of the lagoon, and accelerated downgradient of the impoundment. This change in the velocity field might result in reduced time of travel for pollutants moving to receptor wells downgradient of the impoundment site, which could in turn lead to reductions in pollutant

degradation prior to human exposure. Accurate accounting of the influence of mixing and degradation would require a fully three-dimensional flow and transport model. This methodology uses a simpler approach to estimate a conservative limit to pollutant decay within the system. The limit is estimated by increasing the estimated velocity of ground water flow to account for the maximum downgradient increase in velocity due to the source so that velocity increase can be approximated by idealizing the lagoon as a circular source, so that the rate at which seepage passes outward through a cylinder beneath the perimeter of the impoundment's floor to be expressed as:

$$v_i = \frac{Q_{sep} d_a}{4 d_a} \quad (92)$$

where:

- v_i = superimposed radial velocity from water seeping from impoundment (m/sec), and
- Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)
- d_a = depth of aquifer (m)

In addition to increasing the expected velocity of pollutant transport through the aquifer, this superimposed velocity would also have the effect of increasing AT123D's estimate of pollutant dilution within the aquifer. This additional dilution effect must be subtracted back out of the model calculations since the true dilution is explicitly included in the factor introduced by Equation 91. The model performs this calculation automatically based on the following equation for the anti-dilution factor:

$$D_{af} = \frac{(v_v + v_h)}{v_h} \quad (93)$$

where:

- D_{af} = anti-dilution factor (unitless)
- v_v = the vertical velocity due to the source (m/sec)
- v_h = the regional velocity of horizontal ground water flow (m/sec)

It should be noted that the above methodology is conservative since it overestimates the velocity beneath the source and does not allow for decreases in the superimposed velocity beyond the source. As a result, the methodology is more conservative than a three-dimensional model. In comparison with a two-dimensional cross-sectional flow and transport model, the methodology is more conservative beneath the source but less conservative beyond the source.

By combining the VADOFT module with AT123D and adjusting calculations in AT123D to accommodate the dilution and superimposed velocity described above, concentrations of a pollutant in ground water at a receptor well can be predicted as a function of the following factors: the liquid concentration of pollutants near the floor of the impoundment; the rate of seepage from the facility; and hydrogeological characteristics of the area. It should be noted that all of the calculations described above are linear with respect to pollutant concentrations in liquid seeping from the impoundment. It is convenient to perform the calculations based on the assumption of a "unit" concentration of dissolved pollutant in seepage beneath the facility.

For the solute transport component of model execution, the flux of pollutant into the top of the unsaturated zone is represented as a pulse of constant magnitude or (e.g., square wave). The duration of this pulse is calculated so that the entire mass of pollutant will be depleted at the equilibrium rates calculated for the active impoundment:

$$TP = \frac{TF}{f_{act}} 3.2 \times 10^{-3} \quad (94)$$

where:

TP	=	duration of square wave for approximating the loading of pollutant into the top of the unsaturated soil zone (yr)
TF	=	duration of facility's active lifetime (sec)
3.2×10^{-3}	=	conversion factor (yr) (sec) ⁻¹
f_{act}	=	fraction of pollutant lost during surface impoundment's active phase (unitless)

This result is combined with pollutant-specific properties and assumptions about the physical characteristics of the unsaturated and saturated zones to provide inputs for the linked VADOFT and AT123D models. Model results include an estimate of the maximum concentration of pollutant expected in a well at the downgradient property boundary of the site within the 300-year period simulated. This estimate is divided by the assumed concentration of pollutant in seepage from the facility to estimate a ratio between these two concentrations:

$$f_{wel} = \frac{C_{wel}}{C_{sep}}$$

where:

- f_{wel} = ratio of predicted concentration in well to assumed concentration in seepage (unitless)
 C_{wel} = predicted concentration of pollutant in well (mg/l)
 C_{sep} = assumed concentration of pollutant in seepage (mg/l)

Since calculations in both the VADOFT and AT123D components of the ground-water pathway model are linear with respect to pollutant concentration in seepage beneath the site. The above ratio can be used to back-calculate a reference concentration of pollutant in seepage:

$$RC_{sep} = \frac{RC_{gw}}{f_{wel}} \quad (96)$$

where:

- RC_{sep} = reference concentration of pollutant in water seeping from the bottom of the surface impoundment (mg/l)
 RC_{gw} = reference concentration for pollutant in groundwater (kg/m³)
 f_{wel} = ratio of predicted concentration in well to assumed concentration in seepage (unitless)

Next, multiplying this reference concentration (mg/l) by the weighted average estimate of fluid flux (m/sec) and adjusting units yields the reference flux of pollutant mass from the site:

$$RF_{gw} = 3.2 \times 10^8 RC_{sep} Q_{sep} \quad (97)$$

where:

- RF_{gw} = reference annual flux of pollutant beneath the site (kg/ha • yr)
 3.2×10^8 = conversion factor (kg/ha • yr) [(mg • m)/(l • sec)]⁻¹
 RC_{sep} = reference concentration of pollutant in water seeping from the bottom of the surface impoundment (mg/l)
 Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)

This allowable flux must be related to the dry-weight concentration of sewage sludge entering the impoundment. Because f_{sep} describes the fraction of total pollutant mass seeping from the impoundment and TP provides a lower-bound estimate for the amount of time required to release all significant pollutant from the facility, the reference flux can be converted to an equivalent concentration in sewage sludge by

$$RCS = \frac{TP RF_{gw} 100}{f_{sep} S_2 d_{tot}} \quad (98)$$

where:

- RCS = reference dry-weight concentration of pollutant in sewage sludge (mg/kg)

TP	=	length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant at site (yr)
RF _{gw}	=	reference annual flux of pollutant beneath the site (kg/ha•yr)
100	=	conversion factor (mg/m ²) (kg/ha)
f _{sep}	=	fraction of total pollutant loss attributable to seepage (unitless)
S ₂	=	solids concentration in the sediment layer of a surface impoundment (kg/m ³)
d _{tot}	=	total depth of surface impoundment (m)

5.4.3 Methodology for Vapor Pathway

The vapor pathway of potential exposure is considered for organic pollutants only. The first step is to determine a reference air concentration for each pollutant of concern:

$$RC_{air} = \frac{1000 RL BW}{I_a q_1} \quad (99)$$

where:

RC _{air}	=	reference air concentration for pollutant (μg/m ³)
1000	=	conversion factor (μg) (mg) ⁻¹
RL	=	risk level (incremental risk of cancer per lifetime)
BW	=	body weight (kg)
I _a	=	inhalation volume (m ³ /day)
q ₁	=	human cancer potency (kg•day/mg)

The next step is to relate releases of volatilized pollutant from the site to the expected concentration in ambient air. The model used to describe transport of pollutant from a monofill is described in (U.S. EPA, 1986d) and is based on equations described in Environmental Science and Engineering (1985). The highly exposed individual (HEI) is assumed to live at the downwind property boundary of the surface impoundment. A source-receptor ratio is calculated to relate the concentration of pollutant in ambient air at the HEI's location (g/m³) to the rate that pollutant is emitted from the treated soil (g/m²•sec).

$$SRR = 2.032 \frac{A v}{(r' + x_y) \omega \sigma_z} \quad (100)$$

where:

SRR	=	source-receptor ratio (sec/m)
2.032	=	empirical constant
A	=	area of surface impoundment (m ²)
v	=	vertical term (unitless)
r'	=	distance from the impoundment center to the receptor (m)
x _y	=	lateral virtual distance (m)
ω	=	wind speed (m/sec)
σ _z	=	standard deviation of the vertical concentration distribution (m)

The vertical term (v) is a function of source height, the mixing layer height and σ_z. Under stable conditions the mixing layer height is assumed infinite. Thus, given also a pollutant release height of zero, v=1.

The lateral virtual distance is the distance from a virtual point source to the surface impoundment, such that the angle θ subtended by the surface impoundment's width is 22.5°. This distance is calculated as:

$$x_y = \sqrt{\frac{A}{\pi}} \cot \frac{\theta}{2} \quad (101)$$

where:

x _y	=	lateral virtual distance (m)
A	=	area of surface impoundment (m ²)

The standard deviation of the vertical distribution of concentration (σ_z) is defined by an atmospheric stability class and the distance from the center of the impoundment to the receptor. Parameter values for a and b are listed in Table 5-1 of Section 5.3. Using values from this table for stable atmospheric conditions an appropriate value of σ_z can be calculated as:

$$\sigma_z = a x^b \quad (102)$$

such that:

$$x = 0.001 r' \quad (103)$$

where:

σ _z	=	standard deviation of the vertical concentration distribution (m)
r'	=	distance from the impoundment center to the receptor (m)
0.001	=	conversion factor (km) (m) ⁻¹
a	=	first coefficient for calculating σ _z
b	=	second coefficient for calculating σ _z

Dividing the reference air concentration by this source-receptor ratio and adjusting units yields a reference annual flux of emitted pollutant:

$$RF_{air} = \frac{316 RC_{air}}{SRR} \quad (104)$$

where:

RF_{air}	=	reference annual flux of pollutant to air to the site (kg/ha•yr)
316	=	conversion factor ($\mu\text{g}/\text{m}^3 \cdot \text{sec}$) ($\text{kg}/\text{ha} \cdot \text{yr}$) ⁻¹
RC_{air}	=	reference concentration for pollutant in air ($\mu\text{g}/\text{m}^3$)
SRR	=	source-receptor ratio (s/m)

Pollutant limits for the vapor pathway are based on the highest average concentrations of pollutants to be encountered over an expected human lifetime. At the rate at which pollutant is lost during the facility's active operation, the fraction that would be lost to all processes over a period equivalent to the life expectancy is:

$$f_{ls} = \frac{LS}{TP} \quad (105)$$

where:

f_{ls}	=	fraction of total pollutant lost during human lifetime (unitless)
LS	=	life expectancy (yr)
TP	=	length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant at site (sec or yr)

The reference annual flux multiplied by the human life expectancy yields the total reference mass of pollutant emitted from one hectare of surface impoundment during the period of concern. That mass can be divided by the fraction of pollutant mass volatilized during that period and the dry mass of sewage sludge in one hectare of impoundment to yield (after adjusting units) a reference dry-weight concentration of pollutant in sewage sludge:

$$RCS = \frac{RF_{air} LS}{f_{ls} 100 S_2 d_{tot}} \quad (106)$$

where:

RCS	=	reference dry-weight concentration of pollutant in sewage sludge (mg/kg)
RF_{air}	=	reference annual flux of pollutant to air above the site (kg/ha•yr)
LS	=	life expectancy (yr)
f_{ls}	=	fraction of total pollutant lost during human lifetime (unitless)

100	=	conversion factor (kg/ha) (mg/m ²) ⁻¹
S ₂	=	solids concentration in the sediment layer of a surface impoundment (kg/m ³)
d _{tot}	=	total depth of surface impoundment (m)

5.4.4 Surface Impoundment Prototype Sample Calculations for Pollutant Criteria

5.4.4.1 Mass Balance Calculations

Algorithms for deriving pollutant limits for the surface impoundment prototype will be illustrated with sample calculations for PCBs using parameter values discussed in Section 5.8 and listed in Tables 5-10 through 5-14 (Section 5.7). The first step in mass balance calculations for this prototype is to estimate the concentration of solids in the liquid and sediment layers:

$$\begin{aligned}
 S_1 &= \frac{\rho_{sl}(\text{kg/m}^3) \rho_w(\text{kg/m}^3) P_1(\text{kg/kg})}{\rho_w(\text{kg/m}^3) P_1(\text{kg/kg}) + [1 - P_1(\text{kg/kg})] \rho_{sl}(\text{kg/m}^3)} \\
 &= \frac{(1200)(1000)(0.03)}{(1000)(0.03) + (1 - 0.03)(1200)} \\
 &= 30(\text{kg/m}^3)
 \end{aligned}
 \tag{107}$$

and:

$$\begin{aligned}
 S_2 &= \frac{\rho_{sl}(\text{kg/m}^3) \rho_w(\text{kg/m}^3) P_2(\text{kg/kg})}{\rho_w(\text{kg/m}^3) P_2(\text{kg/kg}) + [1 - P_2(\text{kg/kg})] \rho_{sl}(\text{kg/m}^3)} \\
 &= \frac{(1200)(1000)(0.175)}{(1000)(0.175) + (1 - 0.175)(1200)} \\
 &= 180(\text{kg/m}^3)
 \end{aligned}
 \tag{108}$$

where:

S ₁	=	concentration of solids in liquid layer (kg/m ³)
ρ _{sl}	=	particle density of sewage sludge (kg/m ³)
ρ _w	=	density of water (kg m ³)
P ₁	=	fraction solids in liquid layer (kg/kg)
S ₂	=	concentration of solids in sediment layer (kg/m ³)
P ₂	=	fraction solids in sediment layer (kg/kg)

The volume of outflow from the facility (Q_o) is calculated as:

$$\begin{aligned}
 Q_o &= Q_i (\text{m}^3/\text{sec}) \left[1 - \frac{S_1 (\text{kg}/\text{m}^3)}{\rho_{sl} (\text{kg}/\text{m}^3)} \right] - Q_{sep} (\text{m}/\text{sec}) A (\text{m}^2) \\
 &\quad - DV (\text{m}^3/\text{sec}) \left[1 - \frac{S_2 (\text{kg}/\text{m}^3)}{\rho_{sl} (\text{kg}/\text{m}^3)} \right] \\
 &= (0.0022) \left(1 - \frac{30}{1200} \right) - (7.9 \times 10^{-8}) (20,236) - (3.8 \times 10^{-4}) \left(1 - \frac{175}{1200} \right) \\
 &= 2.3 \times 10^{-4} (\text{m}^3/\text{sec})
 \end{aligned} \tag{109}$$

where:

Q_o	=	rate at which outflow leaves the impoundment (m^3/sec)
Q_i	=	rate of inflow for sludge into a surface impoundment (m^3/sec)
S_1	=	concentration of solids in liquid layer (kg/m^3)
ρ_{sl}	=	particle density of sewage sludge (kg/m^3)
Q_{sep}	=	rate of seepage beneath the impoundment (m^3/sec)
DV	=	rate of change in the volume of the layer, positive for the sediment layer negative for the liquid layer (m^3/sec)
S_2	=	concentration of solids in sediment layer (kg/m^3)

In each layer, pollutant is partitioned between adsorbed and dissolved phases according to the pollutant-specific partition coefficient and the concentration of solids in the layer:

$$\begin{aligned}
 f_{dl} &= \frac{1}{1 + KD (\text{m}^3/\text{kg}) S_1 (\text{kg}/\text{m}^3)} \\
 &= \frac{1}{1 + (468) (30)} \\
 &= 7.1 \times 10^{-5}
 \end{aligned} \tag{110}$$

where:

f_{dl}	=	fraction of pollutant dissolved in liquid layer (unitless)
KD	=	equilibrium partition coefficient for the pollutant (m^3/kg)
S_1	=	concentration of solids in liquid layer (kg/m^3)

For volatilization, the equation for estimating mass transfer in liquid is based on both wind speed and the ratio of fetch to depth. The ratio of fetch to depth is calculated as:

$$FD = \frac{d_e}{d_l} = \frac{161}{2} = 80 \quad (111)$$

FD = ratio of effective diameter to depth of surface impoundment (unitless)
 d_e = effective diameter, or "fetch" (m)
 d_l = depth of liquid layer in surface impoundment (m)

and:

$$d_e = 2\sqrt{\frac{A}{\pi}} = 2\sqrt{\frac{20,236}{3.14}} = 161 \quad (112)$$

d_e = effective diameter, or "fetch" (m)
 A = surface area of surface disposal facility (m²)

Because the assumed wind speed is greater than 3.25 m/sec and the ratio of fetch to depth is greater than 51.2, the mass transfer coefficient for liquid is calculated as in equation 77:

$$\begin{aligned} K_l (\text{m/sec}) &= 2.611 \times 10^{-7} \omega_{10}^2 \left[\frac{D_{cw}}{D_{eth}} \right]^{2/3} \\ &= 2.611 \times 10^{-7} (4.5)^2 \left[\frac{4.2 \times 10^{-6}}{8.5 \times 10^{-6}} \right]^{2/3} \\ &= 3.3 \times 10^{-6} (\text{m/sec}) \end{aligned} \quad (113)$$

where:

K_l = mass transfer coefficient for liquid layer (m/sec)
 ω_{10} = wind velocity at 10 meters altitude (m/sec)
 D_{cw} = diffusivity of pollutant in water (cm²/sec)
 D_{eth} = diffusivity of diethyl ether in water (cm²/sec)

The mass transfer coefficient for gas requires the Schmidt number, defined as:

$$\begin{aligned} Sc_g &= \frac{\mu_a (\text{g/cm} \cdot \text{sec})}{\rho_a (\text{g/cm}^3) D_a (\text{cm}^2/\text{sec})} \\ &= \frac{(1.8 \times 10^{-4})}{(0.0012)(0.057)} \\ &= 2.63 \end{aligned} \quad (114)$$

where:

Sc_g = Schmidt number on gas side (unitless)

μ_a = viscosity of air (g/cm-sec)
 ρ_a = density of air (g/cm³)
 D_m = diffusivity of constituent in air (cm²/sec)

From Hwang (1985), the mass transfer coefficient for the gas phase is then:

$$\begin{aligned}
 K_g &= 1.8 \times 10^{-3} [\omega_{10} (\text{m/sec})]^{0.78} Sc_g^{-0.67} [d_e (\text{m})]^{-0.11} \\
 &= (1.8 \times 10^{-3}) (4.5^{0.78}) (5.23) (161^{-0.11}) \\
 &= 1.74 \times 10^{-3} (\text{m/sec})
 \end{aligned}
 \tag{115}$$

where:

K_g = mass transfer coefficient for liquid layer (m/sec)
 ω_{10} = wind velocity at 10 meters altitude (m/sec)
 Sc_g = Schmidt number on gas side (unitless)
 d_e = effective diameter, or "fetch" (m)

The overall mass transfer coefficient is calculated as:

$$\begin{aligned}
 K_{\text{voll}} (\text{m/sec}) &= \left[\frac{1}{K_l (\text{m/sec})} + \frac{R (\text{m}^3 \cdot \text{atm} / ^\circ \text{K} \cdot \text{mol}) T (^\circ \text{K})}{H (\text{m}^3 \cdot \text{atm} / \text{mol}) K_g (\text{m/sec})} \right]^{-1} \\
 &= \left[\frac{1}{3.3 \times 10^{-6}} + \frac{(8.21 \times 10^{-5}) (288)}{(3.2 \times 10^{-4}) (0.0017)} \right]^{-1} \\
 &= 2.9 \times 10^{-6}
 \end{aligned}
 \tag{116}$$

where:

K_{voll} = overall mass transfer coefficient for volatilization (m/sec)
 K_l = mass transfer coefficient for the liquid layer (m/sec)
 R = ideal gas constant (8.21 x 10⁻⁵ atm • m³/K • mol)
 T = temperature (K)
 H = Henry's Law constant for pollutant (atm • m³/mol)
 K_g = mass transfer coefficient for gas layer (m/sec)

The "active" period in which the impoundment receives sewage sludge (TF, seconds) is calculated from the mass of solids in the filled impoundment divided by the rate at which solid mass enters the impoundment:

$$\begin{aligned}
 TF &= \frac{d_{\text{tot}}(\text{m}) A(\text{m}^2) S_2(\text{kg/m}^3)}{Q_i(\text{m}^3/\text{sec}) S_1(\text{kg/m}^3)} \\
 &= \frac{(4) (20,236) (180)}{(0.0022) (30)} \\
 &= 2.2 \times 10^8 (\text{sec})
 \end{aligned}
 \tag{117}$$

where:

TF	=	duration of facility's active lifetime (sec)
d_{tot}	=	total depth of surface impoundment (m)
A	=	surface area of surface disposal facility (m^2)
S_2	=	solids concentration in the sediment layer of a surface impoundment (kg/m^3)
Q_i	=	rate of inflow for sludge into a surface impoundment (m^3/sec)
S_1	=	concentration of solids in liquid layer (kg/m^3)

The rate of accumulation can be determined by dividing the total depth of the impoundment by its expected active lifetime:

$$\begin{aligned}
 DV &= \frac{d_{\text{tot}}(\text{m}) A(\text{m}^2)}{TF(\text{sec})} \\
 &= \frac{(4)(20,236)}{(2.2 \times 10^8)} \\
 &= 3.7 \times 10^{-4} (\text{m}^3/\text{sec})
 \end{aligned}
 \tag{118}$$

where:

DV	=	rate at which sediment layer accumulates (m^3/sec)
d_{tot}	=	total depth of impoundment (m).
A	=	surface area of surface disposal facility (m^2).
TF	=	duration of facility's active lifetime (sec)

A coefficient for the total rate at which pollutant mass is lost from the liquid layer (K_{tot} , m^3/sec) is calculated as:

$$\begin{aligned}
K_{tot1} &= Q_o (\text{m}^3/\text{sec}) f_{d1} + K_{deg1} (\text{sec}^{-1}) d_1 (\text{m}) A (\text{m}^2) \\
&\quad + K_{vol1} (\text{m}/\text{sec}) f_{d1} A (\text{m}^2) \\
&\quad + Q_{sep} (\text{m}/\text{sec}) f_{d1} A (\text{m}^2) + DV (\text{m}^3/\text{sec}) \\
&= (0.00023)(7.1 \times 10^{-5}) + (2.0 \times 10^{-11})(2)(20,236) \\
&\quad + (2.9 \times 10^{-6})(7.1 \times 10^{-5})(20,236) \\
&\quad + (7.9 \times 10^{-8})(7.1 \times 10^{-5})(20,236) + (3.7 \times 10^{-4}) \\
&= 3.7 \times 10^{-4} (\text{m}^3/\text{sec})
\end{aligned} \tag{119}$$

where:

K_{tot1}	=	lumped rate coefficient for pollutant loss from the liquid layer of surface impoundment (m^3/sec)
Q_o	=	rate at which outflow leaves the impoundment (m^3/sec)
f_{d1}	=	fraction of total pollutant in liquid layer that is dissolved (unitless)
K_{deg1}	=	rate of pollutant degradation in liquid layer (sec^{-1})
d_1	=	depth of liquid layer (m)
A	=	surface area of impoundment (m^2)
K_{vol1}	=	rate of pollutant volatilization from liquid layer (m/sec)
Q_{sep}	=	rate of seepage beneath the impoundment (m/sec)
DV	=	rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

Of the total mass of pollutant lost from the liquid layer, the fraction lost to each process is:

$$\begin{aligned}
f_{out1} &= \frac{Q_o (\text{m}^3) f_{d1}}{K_{tot1} (\text{m}^3/\text{sec})} = \frac{(2.1 \times 10^{-4})(7.0 \times 10^{-5})}{(3.9 \times 10^{-4})} = 4.3 \times 10^{-5} \\
f_{deg1} &= \frac{K_{deg1} (\text{sec}^{-1}) d_1 (\text{m}) A (\text{m}^2)}{K_{tot1} (\text{m}^3/\text{sec})} = \frac{(2.0 \times 10^{-11})(2)(20,236)}{(3.9 \times 10^{-4})} = 2.2 \times 10^{-3}
\end{aligned} \tag{120}$$

$$f_{vol1} = \frac{K_{vol1} (m/sec) f_{d1} A (m^2)}{K_{tot1} (m^3/sec)} = \frac{(2.9 \times 10^{-6}) (7.0 \times 10^{-5}) (20,236)}{(3.9 \times 10^{-4})} = 0.011$$

$$f_{sep1} = \frac{Q_{sep} (m/sec) f_{d1} A (m^2)}{K_{tot1} (m^3/sec)} = \frac{(7.9 \times 10^{-8}) (7.0 \times 10^{-5}) (20,236)}{(3.9 \times 10^{-4})} = 3.0 \times 10^{-4}$$

$$f_{del1} = \frac{DV (m^3/sec)}{K_{tot1} (m^3/sec)} = \frac{(3.8 \times 10^{-4})}{(3.9 \times 10^{-4})} = 0.986$$

where:

- f_{out1} = fraction of total pollutant lost from liquid layer that is lost in outflow from the impoundment (unitless)
- Q_i = rate of inflow for sludge into a surface impoundment (m^3/sec)
- f_{d1} = fraction of total pollutant in liquid layer that is dissolved (unitless)
- K_{tot1} = lumped rate coefficient for pollutant loss from the liquid layer of surface impoundment (m^3/sec)
- f_{degl} = fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
- K_{degl} = rate of pollutant degradation in liquid layer (sec^{-1})
- d_1 = depth of liquid layer (m)
- A = surface area of impoundment (m^2)
- f_{vol1} = fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)
- K_{vol1} = overall mass transfer coefficient for volatilization from the liquid layer of surface impoundment (m/sec)
- f_{sep1} = fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
- Q_{sep} = rate of seepage beneath the impoundment (m/sec)
- f_{del1} = fraction of total pollutant lost from the liquid layer as a result of the diminishing volume of the liquid layer (unitless)
- DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

For the sediment layer, the fraction of pollutant that is dissolved is first calculated as:

$$f_{d2} = \frac{1}{1 + KD S_2} \quad (122)$$

where:

- f_{d2} = fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)
- KD = equilibrium partition coefficient for pollutant (m^3/kg)
- S_2 = solids concentration in the sediment layer of a surface impoundment (kg/m^3)

A coefficient for the total loss or storage of pollutant (K_{tot} in m^3/sec) is then calculated as:

$$\begin{aligned} K_{tot} &= K_{deg2}(\text{sec}^{-1}) d_2(\text{m}) A(\text{m}^2) + Q_{sep}(\text{m/sec}) f_{d2} A(\text{m}^2) + DV(\text{m}^3/\text{sec}) \\ &= (2.0 \times 10^{-11})(2)(20,236) + (7.9 \times 10^{-8})(1.2 \times 10^{-5})(20,236) + (3.7 \times 10^{-4}) \quad (123) \\ &= 3.7 \times 10^{-4}(\text{m}^3/\text{sec}) \end{aligned}$$

where:

- K_{tot} = lumped rate coefficient for pollutant loss from the sediment layer of surface impoundment (m^3/sec)
- K_{deg2} = rate of pollutant degradation in sediment layer (sec^{-1})
- d_2 = depth of sediment layer (m)
- A = surface area of surface disposal facility (m^2)
- Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)
- f_{d2} = fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)
- DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

As with the liquid layer, this coefficient is partitioned into its individual components:

$$\begin{aligned} f_{deg2} &= \frac{K_{deg2}(\text{sec}^{-1}) d_2(\text{m}) A(\text{m}^2)}{K_{tot}(\text{m}^3/\text{sec})} = \frac{(2.0 \times 10^{-11})(2)(20,236)}{(3.8 \times 10^{-4})} = 2.2 \times 10^{-3} \\ f_{sep2} &= \frac{Q_{sep}(\text{m/sec}) f_{d2} A(\text{m}^2)}{K_{tot}(\text{m}^3/\text{sec})} = \frac{(7.9 \times 10^{-8})(1.2 \times 10^{-5})(20,236)}{(3.8 \times 10^{-4})} = 5.2 \times 10^{-5} \quad (124) \\ f_{del2} &= \frac{DV(\text{m}^3/\text{sec})}{K_{tot}(\text{m}^3/\text{sec})} = \frac{(3.7 \times 10^{-4})}{(3.7 \times 10^{-4})} = 0.998 \end{aligned}$$

where:

- f_{deg2} = fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
- K_{deg2} = rate of pollutant degradation in sediment layer (sec^{-1})
- d_2 = depth of sediment layer (m)
- A = surface area of surface disposal facility (m^2)
- K_{tot} = lumped rate coefficient for pollutant loss from the sediment layer of surface impoundment (m^3/sec)
- f_{sep2} = fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)
- Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)
- f_{d2} = fraction of pollutant in the sediment layer of surface impoundment that is dissolved (unitless)

- f_{de2} = fraction of pollutant reaching the sediment layer that is stored in the accumulating depth of this layer (unitless)
 DV = rate of change in the volume of the layer, positive for sediment layer, negative for liquid layer (m^3/sec)

These results are combined to calculate the fraction of yearly loading of pollutant mass lost during each year of the active phase of the impoundment's operation:

$$\begin{aligned}
 f_{act} &= f_{vol1} + f_{deg1} + f_{out1} + (f_{sep1} + f_{del1})(f_{deg2} + f_{sep2}) \\
 &= (0.011) + (0.0022) + (4.3 \times 10^{-5}) + [(3.0 \times 10^{-4}) + (0.986)][(0.0022) + (5.2 \times 10^{-5})] \\
 &= 0.015
 \end{aligned}
 \tag{125}$$

where:

- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)
 f_{vol1} = fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)
 f_{deg1} = fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
 f_{out1} = fraction of total pollutant lost from liquid layer that is lost in outflow from the impoundment (unitless)
 f_{sep1} = fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
 f_{del1} = fraction of pollutant loss from the liquid layer that is displaced by the accumulating sediment layer (unitless)
 f_{deg2} = fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
 f_{sep2} = fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)

Finally, the fraction of pollutant mass lost through each pathway is calculated, based on the simplifying assumption that the partitioning of pollutant mass during the facility's active operation can be used to represent the partitioning of the entire mass of pollutant in the facility.

For losses to seepage:

$$\begin{aligned}
 f_{sep} &= \frac{(f_{sep1} + f_{del1}) f_{sep2}}{f_{act}} \\
 &= \frac{[(3.0 \times 10^{-4}) + (0.986)] (5.2 \times 10^{-5})}{(0.016)} \\
 &= 0.0033
 \end{aligned} \tag{126}$$

where:

- f_{sep} = fraction of total pollutant lost from the impoundment through seepage (unitless)
- f_{sep1} = fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
- f_{del1} = fraction of pollutant loss from the liquid layer that is displaced by the accumulating sediment layer (unitless)
- f_{sep2} = fraction of pollutant reaching the sediment layer that is lost to seepage (unitless)
- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)

For losses to volatilization:

$$f_{vol} = \frac{f_{vol1}}{f_{act}} = \frac{(0.011)}{(0.015)} = 0.71 \tag{127}$$

where:

- f_{vol} = fraction of total pollutant lost from the impoundment through volatilization (unitless)
- f_{vol1} = fraction of total pollutant lost from liquid layer that is lost to volatilization (unitless)
- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)

For losses to degradation:

$$\begin{aligned}
 f_{deg} &= \frac{f_{deg1} + (f_{sep1} + f_{del1}) f_{deg2}}{f_{act}} \\
 &= \frac{(0.0022) + [(3.0 \times 10^{-4}) + (0.986)] (0.0022)}{(0.016)} \\
 &= 0.28
 \end{aligned} \tag{128}$$

where:

- f_{deg} = fraction of total pollutant lost from the impoundment through degradation (unitless)

- f_{deg1} = fraction of total pollutant lost from liquid layer that is lost to degradation (unitless)
- f_{sep1} = fraction of total pollutant lost from liquid layer that is lost to seepage (unitless)
- f_{del1} = fraction of pollutant loss from the liquid layer that is displaced by the accumulating sediment layer (unitless)
- f_{deg2} = fraction of pollutant reaching the sediment layer that is lost to degradation (unitless)
- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)

For losses to outflow:

$$f_{out} = \frac{f_{out1}}{f_{act}} = \frac{(4.3 \times 10^{-5})}{(0.015)} = 0.0028 \quad (129)$$

where:

- f_{out} = fraction of total pollutant lost from the impoundment through outflow (unitless)
- f_{out1} = fraction of total pollutant lost from liquid layer that is lost in outflow from the impoundment (unitless)
- f_{act} = fraction of pollutant lost during surface impoundment's active phase (unitless)

These results are used to calculate pollutant limit criteria for the ground water and vapor pathways.

5.4.4.2 Pollutant Criteria Calculations for Ground-Water Pathway

Execution of the VADOFT model for simulating flow and transport in the unsaturated zone requires an estimate for the duration of a square wave pulse equivalent to the total mass lost to seepage from the impoundment. For PCBs this duration is calculated as:

$$\begin{aligned} TP &= \frac{TF(sec) \ 3.2 \times 10^{-8}}{f_{act}} \\ &= \frac{(2.2 \times 10^8) (3.2 \times 10^{-8})}{(0.016)} \\ &= 450 \text{ (yr)} \end{aligned} \quad (130)$$

where:

TP	=	duration of square wave for approximating the loading of pollutant into the top of the unsaturated soil zone (yr)
TF	=	duration of facility's active lifetime (sec)
3.2×10^{-8}	=	conversion factor (yr) (sec) ⁻¹
f_{act}	=	fraction of pollutant lost during surface impoundment's active phase (unitless)

This value is used to prepare input for the VADOFT model.

The VADOFT and AT123D models are executed with adjustments for local elevation of the water table. With input values provided in Tables 5-12 through 5-14 (see Sections 5.7 and 5.8), the linked models provide an estimate of 0.478 mg/l for the maximum pollutant concentration in ground water within the 300 years simulated. This estimate is divided by the assumed concentration of pollutant in seepage from the facility (1 mg/l) to estimate a ratio between these two concentrations:

$$\begin{aligned}
 f_{wel} &= \frac{C_{wel}(\text{mg/l})}{C_{sep}(\text{mg/l})} \\
 &= \frac{(0.478)}{(1.0)} \\
 &= 0.478
 \end{aligned}
 \tag{131}$$

where:

f_{wel}	=	ratio of predicted pollutant concentration in well to assumed concentration in seepage (unitless)
C_{wel}	=	predicted concentration in well (mg/l)
C_{sep}	=	assumed concentration in seepage (1 mg/l)

A reference concentration of pollutant in seepage is calculated as:

$$\begin{aligned}
 RC_{sep} &= \frac{RC_{gw}(\text{mg/l})}{f_{wel}} \\
 &= \frac{(4.5 \times 10^{-4})}{(0.478)} \\
 &= 9.5 \times 10^{-4} (\text{mg/l})
 \end{aligned}
 \tag{132}$$

where:

- RC_{sep} = reference concentration of pollutant in water seeping from the bottom of the surface impoundment (mg/l)
 RC_{gw} = reference concentration for pollutant in groundwater (kg/m³)
 f_{wel} = ratio of predicted pollutant concentration in well to assumed concentration in seepage (unitless)

Next, multiplying this reference concentration (mg/l) by the fluid flux (in m/sec) and adjusting units yields the reference flux of pollutant mass from the site:

$$\begin{aligned}
 RF_{gw} &= RC_{sep} \text{ (mg/l)} Q_{sep} \text{ (m/sec)} 3.2 \times 10^8 \\
 &= (9.5 \times 10^{-4}) (7.9 \times 10^{-8}) (3.2 \times 10^8) \\
 &= 2.4 \times 10^{-2} \text{ (kg/ha} \cdot \text{yr)}
 \end{aligned}
 \tag{133}$$

where:

- RF_{gw} = reference annual flux of pollutant beneath the site (kg/ha·yr)
 RC_{sep} = reference concentration of pollutant in water seeping from the bottom of the surface impoundment (mg/l)
 Q_{sep} = seepage rate for both liquid and sediment layers (m/sec)
 3.2×10^8 = constant to convert units ([mg·m]/[l·sec]) to (kg/ha·yr)

This reference flux is related to the dry-weight concentration of sewage sludge entering the impoundment by:

$$\begin{aligned}
 RCS &= \frac{TP \text{ (yr)} RF_{gw} \text{ (kg/ha} \cdot \text{yr)} 100}{f_{lec} S_2 \text{ (kg/m}^3\text{)} d_{tot} \text{ (m)}} \\
 &= \frac{(450) (2.4 \times 10^{-2}) 100}{(0.0033) (180) (4)} \\
 &= 451 \text{ (mg/kg)}
 \end{aligned}
 \tag{134}$$

where:

- RCS = reference dry-weight concentration of pollutant in sewage sludge (mg/kg)
 TP = length of "square wave" in which maximum total loss rate of pollutant depletes total mass of pollutant at site (yr)
 RF_{gw} = reference annual flux of pollutant beneath the site (kg/ha·yr)
 100 = conversion factor (mg/m²) (kg/ha)
 f_{sep} = fraction of total pollutant loss attributable to seepage (unitless)
 S_2 = solids concentration in the sediment layer of a surface impoundment (kg/m³)
 d_{tot} = total depth of surface impoundment (m)

5.4.4.3 Pollutant Criteria Calculations for Vapor Pathway

Pollutant limit criteria for the air pathway are derived for organic pollutants only. For each pollutant, a reference air concentration is first established based on cancer potency:

$$\begin{aligned} RC_{\text{air}} &= \frac{RL \text{ BW(kg)} 1000(\text{ug/m}^3)}{I_a(\text{m}^3/\text{day}) q_1^*(\text{kg} \cdot \text{day}/\text{mg})} \\ &= \frac{(10^{-4}) (70) 1000}{(20) (7.7)} \\ &= 0.045(\mu\text{g}/\text{m}^3) \end{aligned} \tag{135}$$

where:

RC_{air}	=	reference air concentration for pollutant ($\mu\text{g}/\text{m}^3$)
RL	=	risk level (incremental risk of cancer per lifetime)
BW	=	body weight (kg)
1000	=	conversion factor (μg) (mg) ⁻¹
I_a	=	inhalation volume (m^3/day)
q_1^*	=	human cancer potency ($\text{kg} \cdot \text{day}/\text{mg}$)

To relate this reference concentration to a rate of volatile emissions from treated land, a source-receptor ratio is calculated from a vertical term, a lateral virtual distance, and the standard deviation of the vertical distribution of concentrations.

The vertical term (v) is a function of source height, the mixing layer height and σ_z . Under stable conditions the mixing layer height is assumed infinite, and for a pollutant release height of zero, $v=1$.

The lateral virtual distance is the distance from a virtual point source to the impoundment, such that the angle θ subtended by the impoundment's width is 22.5° . This distance is calculated as:

$$\begin{aligned}
 x_y &= \sqrt{\frac{A}{\pi}} \cot\left(\frac{\theta}{2}\right) \\
 &= \sqrt{\frac{20,236}{3.14}} \cot\left(\frac{22.5^\circ}{2}\right) \\
 &= 403 \text{ (m)}
 \end{aligned}
 \tag{136}$$

and:

$$\begin{aligned}
 x &= 0.001 (r') \\
 r' &= 71
 \end{aligned}
 \tag{137}$$

where:

- x_y = lateral virtual distance (m)
- A = area of surface impoundment (m^2)
- r' = distance from the impoundment center to the receptor (m)

An appropriate value of σ_z is calculated as:

$$\begin{aligned}
 \sigma_z &= a x^b \\
 &= 15.209 (0.071)^{0.81558} \\
 &= 1.8 \text{ (m)}
 \end{aligned}
 \tag{138}$$

where:

- σ_z = standard deviation of the distribution of vertical concentrations (m)
- a = first coefficient for calculating σ_z
- b = second coefficient for calculating σ_z

Using these results, a source-receptor ratio (SRR) is calculated to relate the concentration of pollutant in ambient air at the HEI's location (g/m^3) to the rate that pollutant is emitted from the treated soil ($g/m^2 \cdot sec$):

$$\begin{aligned}
 SRR &= 2.032 \frac{A(m^2) v}{[r'(m) + x_y(m)] v(m/sec) \sigma_z(m)} \\
 &= \frac{2.032 (20,236)(1)}{[(71) + (403)](4.5)(1.8)} \\
 &= 11 \text{ (sec/m)}
 \end{aligned}
 \tag{139}$$

where:

- SRR = source-receptor ratio (sec/m)
- 2.032 = empirical constant
- A = area of impoundment (m^2)

v	=	vertical term (unitless)
r'	=	distance from the impoundment's center to the receptor (m)
x_y	=	lateral virtual distance (m)
ω	=	wind speed (m/sec)
σ_z	=	standard deviation of the distribution of vertical concentrations (m)

Dividing the reference air concentration by this source-receptor ratio (and adjusting units) yields a reference annual flux of emitted pollutant:

$$\begin{aligned}
 RF_{\text{air}} &= \frac{316 RC_{\text{air}} (\mu\text{g}/\text{m}^3)}{SRR (\text{sec}/\text{m})} \\
 &= \frac{316(0.045)}{(11)} \\
 &= 1.3 (\text{kg}/\text{ha} \cdot \text{yr})
 \end{aligned}
 \tag{140}$$

where:

RF_{air}	=	reference annual flux of pollutant emitted from the site (kg/ha•yr)
316	=	conversion factor ($\mu\text{g}/\text{m}^2 \cdot \text{sec}$) ($\text{kg}/\text{ha} \cdot \text{yr}$) ⁻¹
RC_{air}	=	reference concentration for pollutant in air ($\mu\text{g}/\text{m}^3$)
SRR	=	source-receptor ratio (s/m)

The fraction of total pollutant lost during a human lifetime is:

$$f_{\text{ls}} = \frac{LS}{TP} \tag{141}$$

where:

f_{ls}	=	fraction of total pollutant lost during human lifetime (unitless)
LS	=	life expectancy (yr)
TP	=	duration of "square wave" for approximating the loading of pollutant into the top of the unsaturated soil zone (yr)

Finally, the reference dry-weight concentration of pollutant in sewage sludge is calculated as:

$$\begin{aligned}
 \text{RCS} &= \frac{\text{RF}_{\text{air}} (\text{kg/ha} \cdot \text{yr}) \text{ LS (yr) (100)}}{f_{\text{vol}} f_{\text{ls}} S_2 (\text{kg/m}^3) d_{\text{tot}} (\text{m})} \\
 &= \frac{(1.3)(70)(100)}{(0.72)(0.16)(180)(4)} \\
 &= 110 (\text{mg/kg})
 \end{aligned}
 \tag{142}$$

where:

RCS	=	reference dry-weight concentration of pollutant in sewage sludge (mg/kg)
RF _{air}	=	reference annual flux of pollutant to air above the site (kg/ha-yr)
LS	=	life expectancy (yr)
f _{ls}	=	fraction of total pollutant lost during human lifetime (unitless)
100	=	conversion factor (kg/ha) (mg/m ²) ⁻¹
S ₂	=	solids concentration in the sediment layer of a surface impoundment (kg/m ³)
d _{tot}	=	total depth of surface impoundment (m)

5.5 RESULTS OF PART 503 RISK ASSESSMENT

This section presents the results of the risk assessment for the monofill and surface impoundment prototypes modelled in support of the Part 503 regulation for surface disposal. Tables 5-2 and 5-3 give the pollutant loading criteria for sewage sludge placed in an unlined monofill and surface impoundment, respectively, located over Class I ground water. The pollutant loading criteria for sewage sludge placed in a lined monofill and surface impoundment located over Class I ground water are shown in Tables 5-4 and 5-5, respectively. Tables 5-6 through 5-9 present the pollutant criteria for sewage sludge placed in unlined and lined monofills and surface improvements located over Class II/III ground water.

5.6 FACTORS RELATED TO RISK ASSESSMENT

This section discusses the risk-based factors related to the risk assessment performed for the surface disposal of sewage sludge. It also explains the concept of the highly exposed individual (HEI) that EPA used as a means to limit human exposure to ground water and vapor potentially containing pollutants resulting from the surface disposal of sewage sludge. In

TABLE 5-2
POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN UNLINED MONOFILL
OVER CLASS I GROUND WATER

Contaminants	Groundwater Pathway	Vapor Pathway
Arsenic	17	#N/A
Benzene	33	6,100
Benzo(a)Pyrene	78,00	unlimited
Bis(2-ethylhexyl)phthalate	44,00	unlimited
Cadmium	360	#N/A
Chlordane	unlimited	unlimited
Chromium	140	#N/A
Copper	4,800	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	2,300	#N/A
Lindane	9,200	unlimited
Mercury	99	#N/A
Nickel	150	#N/A
n-Nitrosodimethylamine	0.022	3,000
PCBs	23,000	unlimited
Toxaphene	unlimited	unlimited
Trichloroethylene	1,500	unlimited

Note: Criteria are expressed in mg per kg.

TABLE 5-3

**POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN UNLINED SURFACE IMPOUNDMENT
OVER CLASS I GROUND WATER**

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	8.8	#N/A
Benzene	19	3,300
Benzo(a)Pyrene	950	unlimited
Bis(2-ethylhexyl)phthalate	550	unlimited
Cadmium	20	#N/A
Chlordane	unlimited	unlimited
Chromium	57	#N/A
Copper	1,200	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	95	#N/A
Lindane	660	28,000
Mercury	7.4	#N/A
Nickel	62	#N/A
n-Nitrosodimethylamine	0.01	15
PCBs	450	110
Toxaphene	unlimited	26,000
Trichloroethylene	340	10,000

Note: Criteria are expressed in mg per kg.

TABLE 5-4
POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN LINED MONOFILL
OVER CLASS I GROUND WATER

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	13,000	#N/A
Benzene	unlimited	6,000
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	unlimited	#N/A
Copper	unlimited	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	unlimited
Mercury	unlimited	#N/A
Nickel	unlimited	#N/A
n-Nitrosodimethylamine	20	2,3000
PCBs	unlimited	unlimited
Toxaphene	unlimited	unlimited
Trichloroethylene	unlimited	unlimited

Note: Criteria are expressed in mg per kg

TABLE 5-5
POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN LINED SURFACE IMPOUNDMENT
OVER CLASS I GROUND WATER

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	35,00	#N/A
Benzene	unlimited	3,400
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	unlimited	#N/A
Copper	unlimited	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	28,000
Mercury	unlimited	#N/A
Nickel	unlimited	#N/A
n-Nitrosodimethylamine	92	16
PCBs	unlimited	110
Toxaphene	unlimited	26,000
Trichloroethylene	unlimited	10,000

Note: Criteria are expressed in mg per kg.

TABLE 5-6
POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN UNLINED MONOFILL
OVER CLASS II/III GROUND WATER

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	140	#N/A
Benzene	1,200	6,100
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	unlimited	#N/A
Copper	unlimited	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	unlimited
Mercury	unlimited	#N/A
Nickel	unlimited	#N/A
n-Nitrosodimethylamine	0.47	3,000
PCBs	unlimited	unlimited
Toxaphene	unlimited	unlimited
Trichloroethylene	unlimited	unlimited

Note: criteria are expressed in mg per kg.

TABLE 5-7

**POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN UNLINED SURFACE IMPOUNDMENT
OVER CLASS II/III GROUND WATER**

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	73	#N/A
Benzene	140	3,300
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	600	#N/A
Copper	46,000	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	28,000
Mercury	unlimited	#N/A
Nickel	690	#N/A
n-Nitrosodimethylamine	0.88	15
PCBs	unlimited	110
Toxaphene	unlimited	26,000
Trichloroethylene	9,500	10,000

Note: Criteria are expressed in mg per kg.

TABLE 5-8
POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN LINED MONOFILL
OVER CLASS II/III GROUND WATER

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	unlimited	#N/A
Benzene	unlimited	6,000
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	unlimited	#N/A
Copper	unlimited	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	unlimited
Mercury	unlimited	#N/A
Nickel	unlimited	#N/A
n-Nitrosodimethylamine	790	2,300
PCBs	unlimited	unlimited
Toxaphene	unlimited	unlimited
Trichloroethylene	unlimited	unlimited

Note: Criteria are expressed in mg per kg.

TABLE 5-9

**POLLUTANT LOADING CRITERIA
FOR SEWAGE SLUDGE DISPOSAL IN LINED SURFACE IMPOUNDMENT
OVER CLASS II/III GROUND WATER**

Contaminant	Groundwater Pathway	Vapor Pathway
Arsenic	unlimited	#N/A
Benzene	unlimited	3,400
Benzo(a)Pyrene	unlimited	unlimited
Bis(2-ethylhexyl)phthalate	unlimited	unlimited
Cadmium	unlimited	#N/A
Chlordane	unlimited	unlimited
Chromium	unlimited	#N/A
Copper	unlimited	#N/A
DDT/DDD/DDE	unlimited	unlimited
Lead	unlimited	#N/A
Lindane	unlimited	28,000
Mercury	unlimited	#N/A
Nickel	unlimited	#N/A
n-Nitrosodimethylamine	3,400	16
PCBs	unlimited	100
Toxaphene	unlimited	26,000
Trichloroethylene	unlimited	10,000

Note: Criteria are expressed in mg per kg.

addition, this section explains the way in which EPA applied its risk assessment methodology to the development of pollutant limits for Subpart C of the sewage sludge regulation.

5.6.1 The Highly Exposed Individual

The risk-based equations developed for the Part 503 regulation were designed to limit potential exposure of an HEI to the pollutants of concern. The HEI is an individual who remains for an extended period of time at the point of maximum ambient ground-level pollutant concentration. For sewage sludge placed on a surface disposal site, total concentration is limited so that the increased risk attributable to each carcinogenic pollutant being regulated does not exceed an additional lifetime risk (70 years) of 1×10^{-4} (1 in 10,000) to the HEI.

The 1989 proposed Part 503 rule considered the exposed individual to be a "most exposed individual" (MEI). EPA changed the terminology to an HEI for the final rule based on a revised exposure assessment analysis. The assessment for the final Part 503 regulation incorporates assumptions that the Agency has concluded present a more realistic characterization of the potential for adverse effects on public health and the environment. These exposure assumptions are designed to limit the potential exposure to an HEI rather than an MEI.

EPA's HEI exposure assessment analysis and the numerical pollutant limits developed from that analysis are designed to address the risk to individuals and populations which may face a greater risk than the general population from exposure to pollutants in sewage sludge. The analysis attempts to evaluate realistic risk by using variables that are reflective of likely experience. This approach does not evaluate the risk associated with a combination of improbable occurrences, as did the MEI approach. EPA concluded that the HEI approach is consistent with its statutory duty to develop regulations that are "adequate to protect public health and the environment from any reasonably anticipated adverse effects." In the case of the surface disposal of sewage sludge, the assumptions used in the risk assessment methodology did not change as a result of the change in terminology from the MEI to the HEI.

In developing Subpart C of the rule, EPA used two variations of the HEI in evaluating each pathway of potential exposure to the toxic effects of pollutants in sewage sludge placed on a surface disposal site. For the vapor pathway, the HEI is assumed to live at or beyond the property boundary of the surface disposal site and inhale 20 m³/day for 70 years. The air dispersion was modeled by an ISCLT plume model or box model. For the ground water pathway, the HEI is assumed to drink 2 liters/day of water containing the pollutant for 70 years. If the surface disposal unit is greater than 150 meters from the property boundary, the HEI is assumed to draw water from a well that is 150 meters from the surface disposal site. If the unit is less than 150 meters from the property boundary, the HEI is assumed to draw water from a well that is whatever distance that unit is from the surface disposal site.

5.6.2 Factors Related to Calculating the Human Dose

5.6.2.1 Maximum Pollutant Level

The maximum pollutant level is the "maximum permissible level of a pollutant in water, which is delivered to the free-flowing outlet of the ultimate user of the public water system, except in the case of turbidity where the maximum permissible level is measured at the point of entry to the distribution system. Pollutants added to the water under circumstances controlled by the user, except those resulting from corrosion of piping and plumbing caused by water quality, are excluded from this definition (40 CFR Part 141)."

5.6.2.2 Cancer Potency

The cancer potency value (q_1^*) represents the relationship between a specified carcinogenic dose and its associated degree of risk. The q_1^* is based on continual exposure of an individual to a specified concentration over a period of 70 years. Established EPA methodology for determining cancer potency values assumes that any degree of exposure to a carcinogen produces a measurable risk. The q_1^* value is expressed in terms of risk per dose and is measured

in reciprocal units of milligrams of pollutant per kilogram of body weight and per day of exposure (mg/kg-day)⁻¹.

EPA previously has calculated cancer potency estimates for arsenic, cadmium, and chromium, which appear in the Agency's Integrated Risk Information System (IRIS) database (U.S. EPA, 1992a). EPA also compiles scientific data on the observed health effects from exposure to a large number of pollutants in its IRIS database. The "most sensitive endpoint" for humans exposed to the three carcinogens regulated in Subpart C are listed in IRIS as follows: arsenic (lung, skin, and gastrointestinal cancers); hexavalent chromium (lung cancer and cancers in other organs); and nickel subsulfide (lung and nasal cancer) (U.S. EPA, 1992a).

5.6.2.3 Risk Level

EPA's regulations are designed to achieve risk levels of between 1×10^{-4} and 1×10^{-7} in a number of regulatory applications, depending on the statute, surrounding issues, uncertainties, and available data bases. In the case of sewage sludge placed in a surface disposal site, EPA chose the 1×10^{-4} risk level, or the probability of 1 cancer case in 10,000 individuals, as a conservative public health goal. This target was selected because the aggregate effects assessment for the final rule, which considers the health effects to the HEI and the population as a whole, showed minimal risk from current sewage sludge surface disposal management practices, even in the absence of regulation.

In determining the appropriate doses to use in the exposure assessment models for carcinogenic pollutants, EPA used the quotient of an incremental risk and the potency value, q_1 . The incremental risk is defined as the probability of an individual contracting cancer following a lifetime of exposure to the maximum modeled long-term ambient concentration. The incremental risk cannot be construed as an absolute measure of the risk to the exposed population because of the uncertainties inherent in determining the cancer potency for each chemical. Furthermore, a case does not indicate the severity of the outcome. An additional cancer case does not necessarily mean a mortality. Therefore, such estimates are best reviewed as relative estimates of the likelihood of cancer.

To reduce this aggregate carcinogenic risk, the Agency chose to regulate sewage sludge surface disposal practices such that each carcinogen present in sewage sludge does not exceed an incremental unit risk of 1×10^{-4} to the HEL. The incremental risk for this practice only considered the surface disposal of sewage sludge and does not consider exposure from other sources, natural or man-made.

5.6.2.4 Relative Effectiveness of Exposure

The relative effectiveness (RE) of exposure value as used in the surface disposal risk assessment is a unitless factor that shows the relative toxicological effectiveness of an exposure by a given route when compared with another route. In addition to route differences, RE can also reflect differences in the exposure conditions. For example, absorption of nickel ingested in water has been estimated to be five times greater than when ingested in food.

5.6.2.5 Duration of Exposure

For each pathway, the exposure was assumed to occur for 70 years based on the Agency-approved estimated 70-year lifespan for adults (U.S. EPA, 1990b).

5.6.2.6 Body Weight

As defined by EPA, lifetime inhalation exposures are estimated for a 70 kg man (154 pounds), which is considered the standard body weight of an adult male (U.S. EPA, 1990b).

5.6.2.7 Inhalation Rate

EPA uses 20 m³/day as the amount of air inhaled long-term by the HEI. The Agency regards this value as the standard inhalation rate of an adult male during a normal day (U.S. EPA, 1990b).

5.7 TECHNICAL PARAMETERS USED TO DERIVE RISK-BASED POLLUTANT CRITERIA—TABLES

This section provides the technical parameters used in the risk assessment to derive the pollutant criteria for the surface disposal of sewage sludge. Tables 5-10 through 5-14 provide the inputs and sources used for each parameter. A more detailed discussion of each parameter value is provided in Section 5.8.

Site and sewage sludge parameters for the monofill and surface disposal prototypes are given in Table 5-10. Table 5-11 provides the soil and hydrologic parameters. Input parameters for VADOFT simulation of flow and pollutant transport through the unsaturated zone are given in Table 5-12. The inputs used in the AT123D simulation of flow and pollutant transport through the saturated zone are given in Tables 5-13 and 5-14 for monofills and surface impoundments, respectively.

5.8 TECHNICAL PARAMETERS USED TO DERIVE RISK-BASED POLLUTANT CRITERIA—DISCUSSION

This section discusses values of the technical input parameters used to derive pollutant criteria for surface disposal. Many input parameters are the same for modeling the monofill and surface impoundment prototypes; where differences occur, separate discussions are provided for each prototype.

TABLE 5-10

**SITE AND SEWAGE SLUDGE PARAMETERS
FOR MONOFILL AND SURFACE IMPOUNDMENT PROTOTYPES**

Parameter	Value	Source
MONOFILL PROTOTYPE		
Area (m ²)	10,000	U.S. EPA (1986e)
Depth of Facility (m)	3.46	U.S. EPA (1986d)
Active Lifetime (yr)	20	U.S. EPA (1986d)
Thickness of Daily Cover (m)	0.3	U.S. EPA (1978)
Thickness of Permanent Cover (m)	1	U.S. EPA (1978)
Time Each Cell Uncovered (hr)	12	U.S. EPA (1986d)
Time Average Cell Contains Sewage sludge (hr)	87,660	U.S. EPA (1986d)
Sewage sludge as Fraction of Monofill's Content (kg/kg)	0.63	U.S. EPA (1978)
Distance to Well		
Class I Aquifer (m)	0	
Class II Aquifer (m)	150	U.S. EPA Policy
Solids Content of Sludge	0.20	U.S. EPA (1978)
SURFACE IMPOUNDMENT PROTOTYPE		
Area (m ²)	20,236	U.S. EPA (1986f)
Depth of Facility (m)	4	Abt Associates Inc. (1989)
Active Lifetime (yr)	7	Calculated
Rate of Inflow (m ³ /sec)	0.0022	U.S. EPA (1986f)
Solids Content of Inflow (kg/kg)	0.03	U.S. EPA (1978)
Solids Content of "Liquid" Layer (kg/kg)	0.03	U.S. EPA (1978)
Solids Content of "Sediment" Layer (kg/kg)	0.175	Abt Associates Inc. (1989) Chaney (1992)
Particle Density of Sewage sludge (kg/m ³)	1200	Calculated
Distance to Well		
Class I Aquifer (m)	0	
Class II Aquifer (m)	150	U.S. EPA Policy
BOTH PROTOTYPES		
Wind Velocity (m/sec)	4.5	U.S. EPA (1990a)
Average Air Temperature (K)	288	U.S. EPA (1986e)

TABLE 5-11
SOIL AND HYDROLOGIC PARAMETERS
FOR MONOFILL AND SURFACE IMPOUNDMENT PROTOTYPES

Parameter	Value	Source
Soil Type	Sand	Policy
Bulk Density of Sewage sludge/Soil (kg/m ³) ^a	1400	Chaney (1992)
Bulk Density for Pure Soil (kg/m ³) ^b	1600	Freeze and Cherry (1979)
Porosity of Sewage Sludge/Soil	0.4	Todd (1980) Carsel and Parrish (1988)
Porosity of Soil Cover (monofill only)	0.4	Todd (1980) Carsel and Parrish (1988)
Saturated Hydraulic Conductivity of Soil (m/hr)	0.61	Carsel and Parrish (1988)
Water Retention Parameters		
θ_r	0.045	Carsel and Parrish (1988)
α (m ⁻¹)	14.5	Carsel and Parrish (1988)
β	2.68	Carsel and Parrish (1988)
Fraction of Organic Carbon in Soil or Sewage sludge		
Sewage sludge	0.31	U.S. EPA (1983c)
Unsaturated Zone	10 ⁻³	U.S. EPA (1986e)
Saturated Zone	10 ⁻⁴	U.S. EPA (1986e)
Depth to Groundwater		
Class I Aquifer (m)	0	Policy
Class II Aquifer (m)	1	Policy
Net Recharge or Seepage		
Monofill Prototype (m/yr)	0.5	U.S. EPA (1986e)
Surface Impoundment Prototype (m/yr)	2.5	U.S. EPA (1987b)
Thickness of Aquifer		
Class I Aquifer (m)	1	Policy
Class II/III Aquifer (m)	5	Policy
Hydraulic Gradient	0.005	U.S. EPA (1986e)

^aAssumed for this analysis to be comparable to soil treated with land-applied sludge.

^bCalculated from porosity and particle density of 2.650 (kg/m³) from Freeze and Cherry (1979).

TABLE 5-12

**INPUT PARAMETERS FOR VADOFT SIMULATION OF FLOW AND POLLUTANT
TRANSPORT THROUGH THE UNSATURATED ZONE
FOR MONOFILL AND SURFACE IMPOUNDMENT PROTOTYPES**

Parameter	Value	Source
Source Area (ha)		
Monofill	1	U.S. EPA (1986e)
Surface Impoundment	2.0236	U.S. EPA (1986f)
Distance to Bottom of Saturated Zone (m)		
Class I, Class II	1, 6	Policy
Input Parameters for Flow Calculations		
Flux at Top Node (m/yr)		
Monofill	0.5	U.S. EPA (1986e)
Surface Impoundment	2.5	U.S. EPA (1987b)
Head at the Bottom Node (m)		
Class I, Class II	1, 5	Policy
Saturated Hydraulic Conductivity (m/yr)	0.61	Carsel and Parrish (1988)
Effective Porosity (unitless)	0.4	Carsel and Parrish (1988)
Specific Storage (unitless)	0	U.S. EPA (1989b)
Residual Water Saturation (unitless)	0.045	Carsel and Parrish (1988)
Power Index - N	-1.0	Carsel and Parrish (1988)
Leading Coefficient - α (m^{-1})	14.5	Carsel and Parrish (1988)
Power Index - β	2.68	Carsel and Parrish (1988)
Power Index - γ	0.62	Carsel and Parrish (1988)
Input Parameters for Transport Calculations		
Longitudinal Dispersivity	1.0	U.S. EPA (1989b)
Effective Porosity	0.4	Carsel and Parrish (1988)
Default Darcy Velocity	0	Carsel and Parrish (1988)
Default Water Saturation	1.0	Carsel and Parrish (1988)
Soil-Water Partition Coefficients	Table 5-15	See Table 5-15
Unsaturated Zone Decay Rates	Table 5-18	See Table 5-18
Molecular Diffusion Coefficients	Table 5-21	See Table 5-21

TABLE 5-13

**INPUT PARAMETERS FOR AT123D SIMULATION OF FLOW AND POLLUTANT
TRANSPORT THROUGH THE SATURATED ZONE
FOR MONOFILL PROTOTYPE**

Parameter	Value	Source
Source Area (ha)	1	U.S. EPA (1986e)
Distance to receptor well (m)		
Class I	0	Policy
Class II	150	Policy
Aquifer width	infinite	AT123D
Aquifer depth (m)		
Class I	1	Policy
Class II	5	Policy
Begin point of x-source location (m)	0	Based on source Area
End point of x-source location (m)	100	Based on source area
Begin point of y-source location (m)	50	Based on source area
End point of y-source location (m)	50	Based on source area
Effective porosity	0.4	Carsel and Parrish (1988)
Hydraulic conductivity (m/yr)	0.61	Carsel and Parrish (1988)
Hydraulic gradient (m/m)	0.005	U.S. EPA (1986e)
Longitudinal dispersivity (m)	15.3	U.S. EPA (1986f)
Lateral dispersivity (m)	5.1	U.S. EPA (1986f)
Vertical dispersivity (m)	1.0	U.S. EPA (1986f)
Distribution coefficient	Table 5-15	See Table 5-15
Decay rate	Table 5-19	See Table 5-19
Bulk density of soil (kg/m ³)	1600	Based on particle density of 2.65 and model porosity
Density of water (kg/m ³)	1000	

TABLE 5-14

**INPUT PARAMETERS FOR AT123D SIMULATION OF FLOW AND POLLUTANT
TRANSPORT THROUGH THE SATURATED ZONE
FOR THE SURFACE IMPOUNDMENT PROTOTYPE**

Parameter	Value	Source
Source Area (m ²)	20,236	U.S. EPA (1986f)
Distance to receptor well (m)		
Class I	0	Policy
Class II	150	Policy
Aquifer width	Infinite	AT123D
Aquifer depth (m)		
Class I	1	Policy
Class II	5	Policy
Begin point of x-source location (m)	0	Based on source area
End point of x-source location (m)	142	Based on source area
Begin point of y-source location (m)	71	Based on source area
End point of y-source location (m)	71	Based on source area
Effective porosity	0.4	Carsel and Parrish (1988)
Hydraulic conductivity (m/yr)	0.61	Carsel and Parrish (1988)
Hydraulic gradient (m/m)	0.005	U.S. EPA (1986e)
Longitudinal dispersivity (m)	15.3	U.S. EPA (1986f)
Lateral dispersivity (m)	5.1	U.S. EPA (1986f)
Vertical dispersivity (m)	1.0	U.S. EPA (1986f)
Distribution coefficient	Table 5-15	See Table 5-15
Decay rate	Table 5-19	See Table 5-19
Bulk density of soil (kg/m ³)	1600	Based on particle density of 2.65 and model porosity
Density of water (kg/m ³)	1000	

5.8.1 Site Parameters

For both monofills and surface impoundments, EPA assumed that the sludge is placed entirely beneath the ground surface, requiring subsurface excavation. For monofills, the excavated soil is typically piled next to the trench and used for cover. For simplicity, it is assumed that the geometry of the site is square for both prototypes: the length of each side is equal to the square root of the site's surface area. Values for input parameters used to characterize surface disposal facilities are listed in Table 5-10 for the monofill and surface impoundment prototypes.

5.8.1.1 Area of the Disposal Site

The area for the monofill prototype is set to 1 hectare (10,000 m²), based on a design scenario described in U.S. EPA (1986e). The model area of a surface impoundment is set to 20,236 m². This value represents the 98th percentile of areas for surface impoundments, as reported in the RCRA Subtitle D survey (U.S. EPA, 1986f).

5.8.1.2 Depth of Disposal Facility

The depth of a monofill determines the total quantity of sludge contained in the site. The assumed depth of 3.46 m (10 ft) is based on a design scenario described in U.S. EPA (1986d). The depth of the surface impoundment is assumed to be 4 m. This value represents the average of data collected from an informal survey of municipal sewage sludge practices by Abt Associates Inc. (1989). Based on analysis of data from the 1988 NEEDS Survey, Abt Associates contacted sewage sludge coordinators in the nine states with the largest number of surface impoundments.

5.8.1.3 Distance to Well

For both the monofill and surface impoundment prototypes, the receptor well is conservatively assumed to be located in the direction of ground water flow. For facilities located above a Class I aquifer, it is conservatively assumed to be located at the edge of the site, or a distance of 0 m downgradient from the monofill or surface impoundment. To determine an appropriate distance for a Class II/III aquifer, the Agency used results from a survey of 163 permit applications for land disposal of hazardous waste (U.S. EPA, 1986e) to conclude that 150 meters from the downgradient edge of the site is a reasonable assumption for the point of effective potential human exposure.

5.8.1.4 Thickness of Cover

The thickness of the active cover is assumed to be 0.3 m and the thickness of the final cover 1 meter. These values represent typical thicknesses for cover applied to an area-fill trench (U.S. EPA, 1978).

5.8.1.5 Number of Days Average Cell Uncovered

Total emissions from a monofill cell depend on the length of time the cell is uncovered or covered with a soil layer. For deriving criteria, it is assumed that a cell is open for 4 hours a day for the 3 consecutive days it receives sludge (U.S. EPA, 1986d). For the remaining 20 hours of each of those 3 days, and for the remainder of the active lifetime of the facility, the cell is covered with a temporary layer of soil. During the 20-year active lifetime of the monofill, half the cells will contain sewage sludge for more than 10 years and half for less than 10 years. A typical cell is, therefore, uncovered for $3 \times 4/24$ or 0.5 days and covered for $(20 \times 365.25)/2 - 0.5$, or about 3,652 days. After the facility is filled to capacity, it is covered with a thicker, permanent layer of soil for the remainder of the period simulated.

5.8.1.6 Inflow Rate

As explained in Section 5.2, the prototype facility for surface impoundments is assumed to receive continuous inflow of sewage sludge throughout its active lifetime. The duration of that active lifetime depends on the rate at which sludge enters the facility, the solids content of that sludge, and the volume of the facility. According to the RCRA Subtitle D survey (U.S. EPA, 1986f), almost 96 percent of the sludge lagoons surveyed received less than 50,000 gallons per day ($0.0022 \text{ m}^3/\text{sec}$) of wastewater flow. This value is consistent with the mean inflow rate for surface impoundments, based on the data from the analytic survey of the NSSS, and is used as the model inflow rate.

5.8.1.7 Ratio of Sludge Volume to Total Volume

A typical trench monofill is composed of numerous parallel trenches filled with sludge and separated by soil, so that the entire monofill site contains both sludge and soil. To derive criteria, these layers of sludge and soil are not modeled separately, but are instead idealized as a homogeneous mixture. To calculate the total quantity of sewage sludge likely to be contained within a monofill of specified dimensions, it is necessary to specify the fraction of the monofill's contents consisting of sludge. U.S. EPA (1978) describes several design scenarios for different types of trench monofills and reports the approximate quantity of sludge that can be received per acre for each scenario. The wide-trench monofill scenario (which receives the most sludge per unit area) is reported to receive about $7,744 \text{ m}^3$ of sludge per hectare and to have a depth of about 1.22 m. Dividing this volume of sludge by the volume of facility per hectare ($10,000 \text{ m}^2 \times 1.22 \text{ m}$ or $12,200 \text{ m}^3$) yields the fraction of the monofill's volume that contains pure sludge (0.63).

For the surface impoundment prototype, the entire facility is assumed to be filled with sludge, so that the volume of sludge contained by the facility is equal to the volume of the impoundment.

5.8.1.8 Site Life

The site life for monofills is the length of time the monofill is receiving sewage sludge, up until the time that a permanent cover is applied. The assumed site life of 20 years is based on the design scenario described in U.S. EPA (1986d).

For surface impoundments, the site life is the time required to fill the impoundment with sewage sludge solids, which is calculated from the inflow rate, the percent solids in the sludge, and the dimensions of the facility. Using the inflow rate, percent solids, and site dimensions, the expected lifetime is calculated to be about 7 years.

5.8.1.9 Wind Velocity

Wind velocity affects the transport of volatilized pollutant. As explained in Section 5.3, the equations used to model emissions from monofills require an estimate of average wind velocity at the ground level. For surface impoundments, wind velocity is specified at 10 m above the surface. Although wind velocities at 10 m are likely to be somewhat higher than those at ground level, a single value of 4.5 m/sec (10 mph) has been assumed for both prototypes. This value represents a typical yearly average wind speed in the United States (U.S. EPA, 1990a).

5.8.1.10 Air Temperature

The model air temperature of 15° C represents a typical annual average value for the United States. This value is consistent with the range of temperatures presented in U.S. EPA (1986e).

5.8.2 Sludge Parameters

The physical characteristics of sewage sludge affect the fate and transport of pollutants. In particular, the solids content and particle density of the sludge help determine how much pollutant stays adsorbed to the sludge matrix, and how much is lost to various loss processes. Values for these and other parameters are included in Table 5-10 and are discussed below.

5.8.2.1 Solids Content

The solids content of sewage sludge depends on the level of treatment (i.e., primary, secondary, advanced) and on the types of treatment processes used (e.g., stabilization, dewatering). Only dewatered sludges with solids contents greater than or equal to 15 percent are suitable for disposal in sludge-only monofills. Monofilled sludge is often mixed with a bulking agent (e.g., soil) to increase solids content. The solids content of sludge (20 percent) assumed for deriving national criteria is based on the value reported for a typical wide-trench monofill (U.S. EPA, 1978).

The solids content of sludge deposited in surface impoundments is typically lower than that deposited in monofills. As described in Section 5.4.1, the solids content of sludges within a surface impoundment is assumed to differ between two idealized layers: a "liquid" layer and "sediment" layer. Sewage sludge entering the impoundment is assumed to contain 3 percent solids by mass (0.03 kg/kg). This value falls within the range of concentrations reported for primary and secondary treated sludge (U.S. EPA, 1978). The solids content of the sediment layer is assumed to be 17.5 percent. This value was obtained through a survey of municipal sewage sludge disposal practices by Abt Associates Inc. (1989) and represents the midpoint of solids contents found in surface impoundments after eight or more years. It is also consistent with the range of solids concentrations (15-20 percent) typically encountered within impoundments used to dewater sludge for land application (Chaney, 1992).

5.8.2.2 Particle Density of Sludge

A particle density can be derived from the mass and solids content of a typical wet sludge. According to Chaney (1992), a typical wet sludge in a surface impoundment has a specific gravity of about 1.03, equivalent to a density of about 1030 kg/m³. If 17.5 percent of the mass of such sludge is solids and the remainder is water (with a density of 1000 kg/m³), the particle density of pure sludge (ρ_d) can be calculated as:

$$\rho_{sl} = \frac{(1030)(\text{kg/m}^3) - (1000)(\text{kg/m}^3)(0.825)}{(0.175)} \approx 1200(\text{kg/m}^3)$$

5.8.3 Soil Parameters

The unsaturated zone is characterized by pore space containing both air and water, whereas the pore space in the saturated zone contains water only. Because of differences in fluid mechanics, these two zones require different equations and input parameters for tracking pollutant transport. A simplifying assumption used for deriving criteria is that the basic soil characteristics (including soil type, porosity, and bulk density) of the two zones are identical.

For both the monofill and surface impoundment prototypes, sewage sludge is assumed to be placed entirely beneath the ground surface, requiring subsurface excavation. For monofills, the excavated soil is typically used for cover (U.S. EPA, 1978). Parameter values describing soil and geo-hydrological characteristics for both monofills and surface impoundments (previously listed in Table 5-11 in Section 5.5) are discussed below.

5.8.3.1 Soil Type

The type of soil in the unsaturated and saturated zones affects the ability of a pollutant to move vertically to the aquifer and laterally to a nearby well. In general, the pollution potential of a soil is largely affected by the type of clay present, the shrink/swell potential of that clay, and the grain size of the soil. For example, the less the clay shrinks and swells and the

smaller the grain size of the soil, the less the pollution potential associated with that soil. Soil types in the unsaturated zone in order of increasing pollution potential are: (1) nonshrinking clay, (2) clay loam, (3) silty loam, (4) loam, (5) sandy loam, (6) shrinking clay, (7) sand, (8) gravel, and (9) thin or absent soil (U.S. EPA, 1985e).

Sand has been selected as a reasonable worst-case soil to use in model scenarios for defining numerical criteria for sludge. Wherever possible, all values for parameters describing soil characteristics for model simulations are based on values estimated for sand.

5.8.3.2 Porosity of Sludge/Soil

Porosity is the ratio of the void volume of a given soil or rock mass to the total volume of that mass. If the total volume is represented by V_t and the volume of the voids by V_v , the porosity can be defined as $\theta_t = V_v/V_t$. Porosity is usually reported as a decimal fraction or percentage, and ranges from 0 (no pore space) to 1 (no solids). For soil types with small particle sizes such as clay, porosity increases to a maximum of around 50 percent. Porosities of coarser media like gravel decrease to a minimum of around 30 percent.

To derive pollutant criteria, a total porosity of 0.4 has been taken from Todd (1980). This value is consistent with the average value for sand (0.43) reported in Carsel and Parrish (1988). It is used to represent total porosity within a monofill, in the cover soil applied to a monofill, and within the unsaturated and saturated soil zones beneath both monofill and surface impoundment prototypes.

Effective porosity is calculated as the difference between the average saturated water content and the approximate average residual water content, and refers to the amount of interconnected pore space available for fluid flow. To derive the criteria, average residual water content in the unsaturated zone is assumed to be less than 0.05, and effective porosity has been approximated with the same value used for total porosity (0.4) in mass balance and ground water transport calculations.

5.8.3.3 Bulk Density of Soil

The bulk density of soil is defined as the mass of dry soil divided by its total (or bulk) volume. Bulk density directly influences the retardation of solutes and is related to soil structure. In general, as soils become more compact, their bulk density increases. Bulk density can be related to the particle density and porosity of a given soil as:

$$BD = \rho_{so}(1 - \theta_t)$$

where:

BD	=	bulk density of soil (kg/m ³),
ρ_{so}	=	particle density of soil (kg/m ³) and
θ_t	=	porosity of soil (dimensionless).

Typical mineral soils have particle densities of about 2,650 kg/m³ (Freeze and Cherry, 1979). This value and a soil porosity of 0.4 suggest a bulk density of about 1,600 kg/m³ for pure soil, which is somewhat higher than the 1,300 to 1,500 kg/m³ range typically encountered for soil mixed with sewage sludge (Chaney, 1992).

5.8.3.4 Porosity of Cover Soil

Because cover soil for a monofill is typically excavated from the site, its total porosity is assumed to be the same as for soil within or beneath the facility (0.4).

5.8.3.5 Saturated Hydraulic Conductivity of Soil

Saturated hydraulic conductivity refers to the ability of soil to transmit water, which is governed by the amount and interconnection of void spaces in the unsaturated or saturated zones. These voids may occur as a consequence of inter-granular porosity, fracturing, or bedding planes. In general, high hydraulic conductivities are associated with a high pollution potential. The value for saturated hydraulic conductivity used for deriving criteria (0.61 m/hr) is the 95th

percentile of a probability distribution for hydraulic conductivity in sand derived by Carsel and Parrish (1988). It thus represents a conservative or "reasonable worst case" value.

5.8.3.6 Unsaturated Hydraulic Conductivity of Soil

The hydraulic conductivity or effective permeability of soil in the unsaturated zone is a function of its moisture content, which is, in turn, a function of the pressure head. These relationships are central to the simulation of water flow through the unsaturated zone. The VADOFT model, used to derive criteria, accepts as input sets of data points describing effective permeability-saturation curves and the saturation-pressure head curves. Alternatively, it accepts van Genuchten water retention parameters defining the curves (U.S. EPA, 1989b; Carsel and Parrish, 1988); this latter parameterization is used for deriving criteria.

Based on soils data from the Soil Conservation Survey (SCS), Carsel and Parrish derived distributions for the three parameters required (Θ_r , α , and β) according to twelve SCS textural classifications (Carsel and Parrish, 1988). Values used for deriving criteria (0.045 , 14.5 m^{-1} , and 2.68 for Θ_r , α , and β , respectively) correspond to the mean values reported for sand.

5.8.3.7 Fraction of Organic Carbon in Soil or Sludge

The model combines the fraction of organic carbon in the soil with each pollutant's organic carbon partition coefficient to determine the partitioning of pollutant between soil and water. In general, a lower fraction of organic carbon implies greater mobility for organic pollutants. The organic carbon content for sludge varies among sludge types, with mean values for various types showing a relatively narrow range of 27.6 to 32.6 percent (U.S. EPA, 1983c). Criteria for surface disposal are calculated based on the mean value of carbon reported for all sludges combined (31 percent). A value of 10^{-3} has been selected for the fraction of organic carbon in the unsaturated zone because it is a typical value for sand, and falls at the lower end of the range ($0.001 - 0.01$) reported for soil beneath hazardous waste disposal facilities (U.S. EPA, 1986e). The fraction of organic carbon in the saturated zone is expected to be lower than that of

the unsaturated zone, and has been assigned a value of 10^{-4} , or one tenth the fraction assumed for the unsaturated zone.

5.8.3.8 Depth to Ground Water

The depth to ground water is defined as the distance from the lowest point of the surface disposal facility to the water table. The water table is itself defined as the subsurface boundary between the unsaturated zone (where the pore spaces contain both water and air) and the saturated zone (where the pore spaces contain water only). It may be present in any type of medium and may be either permanent or seasonal. The depth to ground water determines the distance a pollutant must travel before reaching the aquifer and affects the attenuation of pollutant concentration during vertical transport. As this depth increases, attenuation also tends to increase, thus reducing potential pollution of the ground water.

For Class I aquifers, the model scenarios for both monofill and surface impoundment prototypes are based on a worst-case condition, where the water table occasionally or regularly rises above the bottom of the facility: a value of 0 m is chosen as the depth to ground water. This conservative value has been selected to provide maximum protection for these most sensitive aquifers.

For Class II/III aquifers, criteria are calculated based on a depth to ground water of 1 m. This distance is shorter than is likely to be observed at most actual facilities, and represents a conservative assumption designed to protect aquifers at relatively shallow depths.

5.8.4 Hydrologic Parameters

Key hydrologic parameters include net recharge or seepage, the thickness of the aquifer, and the hydraulic gradient. Values used to derive criteria are included in Table 5-11 and discussed below.

5.8.4.1 Net Recharge or Seepage

The primary source of most ground water is precipitation, which passes through the ground surface and percolates to the water table. Net recharge is the volume of water reaching the water table per unit of land and determines the quantity of water available for transporting pollutants vertically to the water table and laterally within the aquifer. The greater the recharge rate, the greater the potential for pollution, up to the point at which the amount of recharge is large enough to dilute the pollutant. Beyond that point, the pollution potential ceases to increase and may actually decrease (U.S. EPA, 1985f).

For monofills, the selected recharge rate (0.5 m/yr) represents the average of a range of values presented in U.S. EPA (1986e). For surface impoundments, the relatively high water content of sewage sludge can provide an additional source of recharge if water from the sludge seeps through the floor of the impoundment. In impoundments receiving continuous or periodic deposits of sludge, this source may not be depleted during the active lifetime of the facility. Table 5-15 lists seepage rates from municipal lagoons (U.S. EPA, 1987b). The value selected for deriving criteria (2.5 m/yr) represents the average seepage rate for lagoons over sandy soil.

5.8.4.2 Thickness of Aquifer

Saturated zones are considered aquifers unless they lack the permeability to yield sufficient water. Only true aquifers are considered when selecting input parameters for calculating criteria. For deriving criteria, the thickness of the aquifer is assumed to be 1 m for Class I aquifers and 5 m for Class II/III aquifers. These thicknesses are assumed to represent reasonable worst-case conditions and have been selected as a matter of policy to ensure that criteria for sludge are sufficiently protective.

TABLE 5-15

SUMMARY OF MEASURED SEEPAGE RATE FROM MUNICIPAL LAGOON SYSTEMS^a

Water Depth (ft)	Lagoon Type	Underlying Soil	Seepage Rate (in/day)	Seepage Rate (L/m ² -hour)
5	Facultative	Heavy silty clay	0.3	0.32
6	Facultative	Light silty clay	0.29	0.31
5	Facultative	Alkaline silt	0.65	0.69
6	Facultative	Fine sand	1.2	1.3
6	Facultative	Gravel and silt	1.3	1.4
-	--	Sandy soil	0.35	0.37
-	--	Sand and gravel	0.61 ^b	0.65
-	--	Sandy soil	0.34	0.36
-	--	Clay loam and shale	0.3	0.32
-	Maturation	Mica and schist	0.06 - 0.23	0.06 - 0.24
5	Facultative	Silt, sand, marl	0.18	0.19
5	Facultative ^c	Sand, silt, marl	1.07	1.13
5	Evaporation ^d	Sand, silt, marl	0.04 - 0.11	0.04 - 0.12
-	Facultative	Sandy soil	0.12	0.13

^a Source: U.S. EPA (1987b).^b Includes net precipitation/evaporation.^c Used intermittently.^d Sealed with bentonite and soda ash.

5.8.4.3 Hydraulic Gradient

The hydraulic gradient is a function of the local topography, ground-water recharge volumes and locations, and the influence of withdrawals (e.g., well fields). It is also very likely to be indirectly related to properties of porous media. Rarely are steep gradients associated with very high conductivities. No functional relationship exists, however, to express this relationship.

The hydraulic gradient value selected for deriving criteria is 0.005 m/m or 0.5 percent, and is based on an average value for ground waters surveyed for the Hazardous Waste Management System Land Disposal Restrictions Regulation (U.S. EPA, 1986e).

5.8.5 Chemical-Specific Parameters

5.8.5.1 Distribution Coefficients

Pollutant transport in soil systems is influenced by interactions between the pollutant and soil. The affinity of pollutants for soil particles may result from ion exchange on charged sites or adsorption due to surface forces. When the soil's capacity to attract pollutant is exceeded, soluble pollutants will move through the soil at the same velocity as the bulk leachate. The affinity between a soil and a pollutant is characterized by the distribution coefficient (KD). Representative KD values (in L/kg or m³/kg) are defined as the equilibrium ratio of the pollutant concentration in soil (mg/kg) to that in associated water (mg/L or mg/m³). Values used for this analysis are listed in Table 5-16, and discussed below.

For organic pollutants, KD is calculated from a pollutant's partition coefficient between organic carbon and water:

$$KD = KOC f_{oc}$$

where:

KD = equilibrium partition coefficient for pollutant (m³/kg),
KOC = organic carbon partition coefficient (m³/kg), and
f_{oc} = fraction of soil consisting of organic matter.

TABLE 5-16

DISTRIBUTION COEFFICIENTS FOR ORGANIC AND INORGANIC CONTAMINANTS

	Within Surface Disposal Facility (l/kg)	Unsaturated Zone (l/kg)	Saturated Zone (l/kg)
Arsenic	20	20	20
Cadmium	431	431	431
Chromium	59	59	59
Copper	98	98	98
Lead	621	621	621
Mercury	330	330	330
Nickel	63	63	63
Benzene	32.8	0.106	0.0106
Benzo(a)pyrene	139,000	448	44.8
Bis(2-ethylhexyl)phthalate	16,800	54.1	5.41
Chlordane	41,200	133	13.3
DDT	239,000	772	77.2
Lindane	726	2.34	0.234
Nitrosodimethylamine	0.115	0.000371	0.0000371
Polychlorinated biphenyls	467,000	1,510	151
Toxaphene	9,140	29.5	2.95
Trichloroethylene	60.1	0.194	0.0194

Notes: The distribution coefficient for organic pollutants (KD) is the product of the organic carbon partition coefficient (KOC) and the fraction of organic carbon in the medium (f_{oc}). Assumes f_{oc} of 31% within the surface disposal facility and 0.1% and 0.01% in the unsaturated and saturated soil zones, respectively. Distribution coefficients for metals are geometric means of values reported for a "sandy loam" soil in Gerritse et al. (1982).

As discussed in Section 5.8.3.7, f_{oc} values of 0.31, 0.001 and 0.0001 are assumed for the sewage sludge layer, unsaturated zone, and saturated zone, respectively.

The organic carbon partition coefficient for a pollutant can be estimated from its octanol-water partition coefficient, which can be measured in laboratory experiments. Values of KOC used to determine criteria are shown in Table 5-17 and are calculated from the following regression equation by Hassett et al. (1983):

$$\log(KOC) = 0.0884 + 0.909\log(KOW)$$

where:

KOW = octanol-water partition coefficient for pollutant

With the exception of PCBs, the KOW values used for this analysis have been obtained from the CHEMEST procedures in the Graphical Exposure Modelling Systems (GEMS and PCGEMS), U.S. EPA (1988y, 1989d).

Polychlorinated biphenyls (PCBs) are a class of chemicals containing 209 possible congeners. The most common constituent of PCB mixtures is Aroclor 1254, which is dominated by penta-congeners, with about equal amounts of tetra- and hexa-congeners. In a well-aged soil contaminated with PCBs, however, Aroclor 1260, which contains more penta- and hexa-congeners than tetra-congeners, is more representative of the PCBs found (O'Connor, 1992). In order to determine a representative organic carbon partition coefficient for PCBs, an average has been calculated from log KOW coefficients listed in Table 5-18 (from Anderson and Parker, 1990). The log KOW for the penta-congener has been estimated to be approximately 6.5 by noting that the log KOW values are approximately linearly related to the number of chlorines in the congener. Averaging that value with the hexa-congener value gives 6.7 for the log KOW. As with other organic pollutants, the regression equation from Hassett et al., (1983) is used to convert this K_{ow} value to an estimate of KOC.

For metals, values for KD are taken from Gerritse et al. (1982) and represent results of laboratory tests with a sludge-amended sandy topsoil. The values used for each pollutant are

TABLE 5-17

**OCTANOL-WATER AND ORGANIC CARBON PARTITION COEFFICIENTS
FOR ORGANIC CONTAMINANTS**

	Log of Octanol- Water Partition Coefficient^a	Organic Carbon Partition Coefficient^b
Benzene	2.13	106
Benzo(a)pyrene	6.12	448,000
Bis(2-ethylhexyl)phthalate	5.11	54,100
Chlordane	5.54	133,000
DDT	6.38	772,000
Lindane	3.61	2,340
Nitrosodimethylamine	-0.57	0.371
Polychlorinated biphenyls ^c	6.70	1,510,000
Toxaphene	4.82	29,500
Trichloroethylene	2.42	194

^a All values except for PCBs taken from the CHEMEST procedure of the Graphical Exposure Modeling System (GEMS and PCGEMS), U.S. EPA (1988; 1989d).

^b *KOC* for organic contaminants derived from *KOW* with Equation 6 from Chapter 15 of Francis et al. (1983): $\log(KOC) = 0.0884 + 0.909\log(KOW)$.

^c Based on aroclor 1254, the most common PCB in sewage sludge. Derived from O'Connor (1991) and representative values from Anderson and Parker (1990)

TABLE 5-18
OCTANOL-WATER PARTITION COEFFICIENTS
FOR PCBS^a

Congener	Number of Chlorines	Log <i>KOW</i>
2,4'	2	5.1
2,2',5,5'	4	6.1
All Penta	5	6.5 ^b
2,2',4,4',5,5'	6	6.9
Average ^c	5.5	6.7

^a Source: Anderson and Parker (1990).

^b Estimated based on apparent linear relationship between number of chlorines on congener and log *KOW*.

^c Log *KOW* values for penta- and hexa-congeners averaged for representative log *KOW*.

listed in Table 5-6, and are based on the geometric mean of the ranges provided by those authors.

5.8.5.2 Decay Rates

Pollutant concentrations in the subsurface regime may be decreased by various degradation processes, including abiotic hydrolysis and aerobic or anaerobic microbial degradation. Although rates of hydrolysis are dependent only on pH and temperature (and can be estimated with reasonable accuracy), estimates of rates for microbial degradation are fraught with uncertainty. This uncertainty is due to many confounding influences in the field, such as substrate availability (fraction of organic carbon present), temperature, the microbial consortium, and microbial acclimation to a given pollutant. Nevertheless, the range of microbial degradation rates obtained in the laboratory by measuring the rate of disappearance of a pollutant in various soil and water grab samples, soil column studies, etc., provides a rough estimate of the rate that microbial activity is likely to degrade a particular pollutant in the field.

As shown in Table 5-19, this work utilizes several sources for representative microbial degradation rates. Where a range of values is reported by these sources, values from the lower end of the range have been selected to derive estimates most protective of public health. Studies of biodegradation in soil have been favored over studies of biodegradation in aquatic environments. If estimates of only aerobic biodegradation rates are available for a given pollutant, a half-life for anaerobic biodegradation has been conservatively estimated to be four times longer (Howard et al., 1991). However, if available data fail to show any indication that a pollutant degraded in a particular regime, a value of 0 has been assumed for the degradation rate.

For the sludge layer of a monofill or surface impoundment, estimated rates of degradation are based on studies of microbial degradation in anaerobic conditions. For the unsaturated soil zone, aerobic microbial degradation and hydrolysis are assumed to be the two dominant degradation processes. Lindane and trichloroethene are the only two compounds that undergo hydrolysis. Since hydrolysis rates are far more accurately quantifiable than microbial

TABLE 5-19
DEGRADATION RATES

	Aerobic Degradation Rate (yr ⁻¹) ^a	Anaerobic Degradation Rate (yr ⁻¹) ^b	Unsaturated Zone Degradation Rate (yr ⁻¹) ^c	Saturated Zone Degradation Rate (yr ⁻¹) ^d
Benzene	16 ^e	0 ^f	1.6	0.8
Benzo(a)pyrene	0.48 ^g	0.12 ^h	0.048	0.084
BEHP	11 ⁱ	0 ^j	1.1	0.55
Chlordane	0 ^k	36 ⁱ	0	18
Lindane	1.2 ^m	8.3 ⁿ	1.2	4.8
DDT	0.04 ^l	2.5 ^k	0.004	1.3
Nitrosodimethylamine	5.1 ^o	1.3 ^h	0.51	0.9
PCBs	0.063 ^p	0.00063 ^q	0.0063	0.0035
Toxaphene	1.2 ^q	6 ^r	0.12	3.1
Trichloroethene	0.78 ^s	3.3 ^t	0.78	2.0

^a Based on microbial degradation rates, except for lindane and trichloroethene, where hydrolysis rates are used.

^b Based on microbial degradation rates.

^c Estimated as 10% of aerobic biodegradation rates. Hydrolysis rates for lindane and trichloroethene assumed same as aerobic rates.

^d Estimated as the arithmetic average of the unsaturated zone degradation rates and the anaerobic degradation rate.

^e Vaishnav and Babeu. (1987).

^f Horowitz *et al.* (1982).

^g Coover and Sims. (1987).

^h Anaerobic rate assumed to equal 25% of aerobic rate; see text for discussion.

ⁱ Howard *et al.* (1991a).

^j Shelton *et al.* (1984).

^k Castro and Yoshida (1971).

^l Stewart and Chisholm (1971).

^m Ellington *et al.* (1988).

ⁿ Zhang *et al.* (1982).

^o Tate and Alexander (1975).

^p Fries (1989).

^q See text for discussion.

^r Howard (1991b).

^s Dilling *et al.* (1975).

^t Bouwer and McCarthy (1983).

degradation rates, hydrolysis rates are used for these two chemicals. For the other eight organic pollutants, 10 percent of the aerobic biodegradation decay rate is assumed to be appropriate for the unsaturated zone. This decision is based on the scientific observation that f_{ac} tends to decrease with depth in the soil, thereby reducing the amount of suitable substrate for microbial populations that might degrade these chemicals (O'Connor, 1992).

In the saturated zone, all three degradation processes can occur because some ground water is anaerobic and some aerobic. To capture this mix of processes, an arithmetic mean has been calculated from the aerobic and anaerobic biodegradation decay rates discussed above. For lindane and TCE, the only two chemicals where hydrolysis is a significant degradation process, estimated anaerobic decay rates are significantly higher than hydrolysis rates.

For PCBs, it is difficult to assign an anaerobic degradation rate. Highly chlorinated congeners may be partially degraded very slowly in reducing conditions, but then oxidative conditions must be established for further degradation to occur. Inadequate information on anaerobic degradation rates exists in the scientific literature. We have conservatively assumed that anaerobic degradation of PCBs occurs at 1 percent of the aerobic biodegradation rate.

5.8.5.3 Molecular Weight

The values presented in Table 5-20 are standard molecular weights for the pollutants of concern. These weights are used in the vapor loss component of the mass balance program for monofills.

5.8.5.4 Henry's Law Constants

Henry's Law constants are used to calculate the rate at which organic pollutants volatilize from sludge. Determining appropriate values for these constants is complicated by the wide variation in estimates provided by various sources. Table 5-21 shows values taken from four different sources, along with the value selected for this analysis. Whenever possible, values are

TABLE 5-20**MOLECULAR WEIGHTS FOR ORGANIC CONTAMINANTS**

	Molecular Weight
Benzene	78.1
Benzo(a)pyrene	252.3
Bis(2-ethylhexyl)phthalate	390.6
Chlordane	409.8
DDT	354.5
Lindane	290.8
Nitrosodimethylamine	74.1
Polychlorinated biphenyls (Aroclor 1254)	325.1
Toxaphene	431.8
Trichloroethylene	131.4

taken from Lyman et al. (1990); otherwise values are taken from the GEMS data base (U.S. EPA, 1988), the PCGEMS data base (U.S. EPA, 1989d), or the Aquatic Fate Process Data for Organic Priority Pollutants (U.S. EPA, 1982b). The decision process is as follows: if a value is published in Lyman et al. (1990), it is used. If not, but if two values are similar, the mean of those two values is used. If there is no value in Lyman et al. and no two values agree, a measured value is chosen in preference to an estimated one. If only estimated, dissimilar values are available, the value most conservative for ground water (i.e., the lowest Henry's Law constant) is chosen. This last circumstance occurs only for nitrosodimethylamine and bis(2-ethylhexyl)phthalate.

The only exception to the decision process described above is for PCBs, which include a variety of possible congeners with different chemical characteristics. Anderson and Parker (1990) provides a compilation of nondimensional Henry's Law constants for one penta-congener and three hexa-congeners. To derive a representative Henry's Law Constant for PCBs, the three values for hexa-congeners were averaged to a single value that was then averaged with the penta-congener value to obtain the single constant reported in Table 5-21.

For all organic pollutants except PCBs, the dimensioned estimate of Henry's Law Constant reported in Table 5-21 has been converted to an equivalent nondimensional constant based on an assumed temperature of 15°C (288K) and the following equation:

$$\dot{H} = \frac{H}{R T}$$

where:

T	=	Temperature (assumed to be 288K),
R	=	Universal Gas Constant (m ³ -atm/mol-K),
H	=	dimensional Henry's law constant (m-atm/mol), and
\dot{H}	=	non-dimensional Henry's Law constant.

Because Anderson and Parker (1990) report nondimensional values for PCBs at 25°C, the average value derived from this source has been adjusted to an equivalent nondimensional value at 15°C.

TABLE 5-21

HENRY'S LAW CONSTANTS

	GEMS ^(a,b) (atm-m ³ /mol)	PCGEMS ^(c,b) (atm-m ³ /mol)	Lyman et al. ^(d) (atm-m ³ /mol)	Aquatic Fate ^(e,b) (atm-m ³ /mol)	Selected Value ^(f) (dimensionless)	Reference
Benzene	3.5x10 ⁻³	5.6x10 ⁻³ (M)	5.5x10 ⁻³	5.5x10 ⁻³	2.3x10 ⁻¹	(d)
Benzo(a)pyrene	1.9x10 ⁻¹⁰	--	--	--	8.0x10 ⁻⁹	(a)
BEHP	4.4x10 ⁻⁵	1.5x10 ⁻⁵	--	3.0x10 ⁻⁷	1.9x10 ⁻⁵	(a)
Chlordane	--	4.9x10 ⁻⁵ (M)	--	9.4x10 ⁻⁵	3.0x10 ⁻³	(c,e)
DDT	2.8x10 ⁻⁴	--	3.8x10 ⁻⁵	1.6x10 ⁻⁵	1.6x10 ⁻³	(d)
Nitrosodimethylamin e	6.5x10 ⁻⁴	2.6x10 ⁻⁷	--	3.3x10 ⁻⁵	1.1x10 ⁻⁵	(c)
Lindane	4.3x10 ⁻⁶	1.4x10 ⁻⁵	4.8x10 ⁻⁷	--	2.0x10 ⁻⁵	(d)
PCBs	--	--	--	--	1.4x10 ⁻²	(g)
Toxaphene	--	6.0x10 ⁻⁶ (M)	--	2.1x10 ⁻¹	2.5x10 ⁻⁴	(c)
Trichloroethylene	2.9x10 ⁻³	1.0x10 ⁻² (M)	1.0x10 ⁻²	9.1x10 ⁻³	4.2x10 ⁻¹	(d)

^a CHEMEST procedure in U.S. EPA (1988).

^b Unless designated as a measurement (M), values estimated using $\hat{H} = VP/WSOL$ where VP is the vapor pressure and $WSOL$ is the water solubility.

^c CHEMEST procedure in U.S. EPA (1989d).

^d Lyman, Reehl and Rosenblatt, Handbook of Chemical Property Estimation Methods, McGraw-Hill, 1990.

^e U.S. EPA (1982b); Aquatic Fate Process Data for Organic Priority Pollutants.

^f Converted to non-dimensional value using $\hat{H} = H/(RT)$ where $T = 288K$, R is the Universal Gas Constant and H is the dimensional Henry's Law constant.

^g Average values from Anderson and Parker (1990) adjusted to 15°C.

5.8.5.5 Diffusion Coefficients

As discussed in Section 5.4.3, volatilization of pollutant from a surface impoundment is modeled with a mass transfer coefficient derived with a two-layer resistance model. Because pollutant must pass through both the liquid and air to be released into the atmosphere, the overall resistance equals the sum of the liquid and gas phase resistances, which are described as the inverse of mass transport coefficients for each phase. Methods for calculating these mass transfer coefficients are selected according to two types of site characteristics: (1) the ratio of the surface's effective diameter (or "fetch") to its depth and (2) the local average wind speed. Effective diameter is defined as the diameter of a circle of area equal to the facility's. The fetch:depth ratio for the model site is about 80 and is calculated using an effective diameter of 161 m (area = 20,236 m²), and a depth of 2 m (the depth of the liquid layer).

Mass transfer coefficients for the liquid and gas phases are calculated from effective diameter, the fetch:depth ratio, wind velocity, the viscosity and density of air, and the estimated diffusivity of each pollutant in water and air. Default values for the viscosity of air (1.8×10^{-4} g/cm-sec) and the density of air (1.2×10^{-3} g/cm³ at STP) have been taken from Incropera and DeWitt (1985). Wilke and Lee's method provides estimates for the diffusivity of each pollutant in air, and Hayduk and Laudie's method provides estimates for each pollutant's diffusivity in water (Lyman et al., 1990). The resulting estimates, which are based on a temperature of 15°C, are listed in Table 5-22.

5.8.5.6 Reference Water Concentration

The health effects level is defined as the concentration of pollutant in ground water or air used to evaluate the potential for adverse effects on human health as a result of sewage sludge disposal. For the ground water pathway of human exposure, the health effects level is expressed as a reference water concentration or adjusted reference water concentration (RWC, in mg/L), and for the vapor pathway it is expressed as a reference air concentration (RAC, in µg/m³). Criteria for surface disposal of sewage sludge are calculated to result in ground-water

TABLE 5-22

DIFFUSION COEFFICIENTS FOR ORGANIC CONTAMINANTS

	Diffusivity in Air (cm ² /sec) ^a	Diffusivity in Water (cm ² /sec) ^b
Benzene	9.1 x 10 ⁻²	7.8 x 10 ⁻⁶
Benzo(a)pyrene	4.6 x 10 ⁻²	4.3 x 10 ⁻⁶
Bis(2-ethylhexyl)phthalate	3.3 x 10 ⁻²	3.2 x 10 ⁻⁶
Chlordane	4.5 x 10 ⁻²	3.7 x 10 ⁻⁶
DDT	4.1 x 10 ⁻²	3.7 x 10 ⁻⁶
Nitrosodimethylamine	9.3 x 10 ⁻²	8.5 x 10 ⁻⁶
Lindane	5.0 x 10 ⁻²	4.5 x 10 ⁻⁶
Polychlorinated biphenyls	5.7 x 10 ⁻²	4.2 x 10 ⁻⁶
Toxaphene	5.3 x 10 ⁻²	3.6 x 10 ⁻⁶
Trichloroethylene	8.2 x 10 ⁻²	7.3 x 10 ⁻⁶

^a Calculated using the Wilke and Lee method from Chapter 17-4 of Lyman (1990), based on temperature of 15°C.

^b Calculated using the Hayduk and Laudie method from Chapter 17-7 of Lyman (1990), based on temperature of 15°C.

concentrations equal to or less than the RWC, and air concentrations equal to or less than the RAC at the point of compliance. Values for RWC are listed in Table 5-23.

For all pollutants except nitrosodimethylamine, the reference water concentration has been calculated by adjusting the Maximum Pollutant Level (MCL) for background concentrations of pollutant expected in ground water. For nitrosodimethylamine, the RWC has been derived from the human cancer potency, with an equation provided in Section 5.3.2. It is assumed that the highly exposed individual ingests 2 l of water per day and weighs 70 kg. The RWC is calculated based on a risk level of 10^{-4} .

To ensure that well water does not exceed the MCL, any preexisting ground-water concentrations must be considered in addition to pollutant contributions from the surface disposal of sludge. Metals are ubiquitous in the environment and can be expected to occur naturally in ground water; values for background concentrations of inorganic pollutants in ground water are taken from the National Inorganic and Radionuclides Survey. These values (listed in Table 5-23) represent average background levels observed in tap water, but have been used in this analysis to approximate current background concentrations in ground water. Where concentrations of a given metal in a particular sample fall beneath the limit of detection, a value of 1/2 the detection limit has been assigned to the sample to derive these averages. These estimated background concentrations are subtracted from the MCLs to determine the reference water concentration for each pollutant in sludge. Organic pollutants are less likely to be found in uncontaminated sources, so background concentrations are assumed to equal zero.

5.8.5.7 Reference Air Concentration

Values for the Reference Air Concentration of all organic pollutants are calculated from the pollutants' estimated human cancer potencies, as discussed in Section 5.6.2.2. Estimates are based on a risk level of 10^{-4} and a body weight of 70 kg. The highly exposed individual is assumed to inhale 20 m³ of contaminated air daily for his or her entire lifetime. Human cancer potencies and reference air concentrations are listed in Table 5-24.

TABLE 5-23

ADJUSTED REFERENCE WATER CONCENTRATION

	Reference Water Concentration (mg/l) ^a	Background Concentration in Groundwater (mg/l)	Adjusted Reference Water Concentration (mg/l) ^b
Arsenic	0.05	0.0032	0.0468
Cadmium	0.005	0.0011	0.0039
Chromium	0.1	0.0014	0.0986
Copper	1.3	0.0499	1.2501
Lead	0.015	0.0035	0.0115
Mercury	0.002	0.0001	0.0019
Nickel	0.1	0.0030	0.097
Benzene	0.005	0	0.005
Benzo(a)pyrene	0.0002	0	0.0002
Bis(2-ethylhexyl)phthalate	0.004	0	0.004
Chlordane	0.002	0	0.002
DDT ^c	0.0102	0	0.0102
Lindane	0.0002	0	0.0002
Nitrosodimethylamine ^c	0.00007	0	0.00007
Polychlorinated biphenyls	0.000454	0	0.000454
Toxaphene	0.003	0	0.003
Trichloroethylene	0.005	0	0.005

^a All values except those for DDT and nitrosodimethylamine are based on the Maximum Contaminant Level (MCL) under the Safe Drinking Water Act (SDWA).

^b Values represent the Reference Water Concentration less background concentrations (see Sections 5.3 and 5.4)

^c Calculated from human cancer potency at the 10⁻⁴ risk level.

TABLE 5-24

HUMAN CANCER POTENCIES AND REFERENCE AIR CONCENTRATIONS

	Human Cancer Potency (mg/kg-day) ⁻¹	Reference Air Concentration ($\mu\text{g}/\text{m}^3$)
Arsenic	1.75	-
Benzene	0.029	12.0
Benzo(a)pyrene	11.5	0.032
Bis(2-ethylhexyl)phthalate	0.0141	25.0
Chlordane	1.3	0.27
DDT	0.34	1.0
Lindane	51	0.26
Nitrosodimethylamine	1.33	0.0071
Polychlorinated biphenyls	7.7	0.045
Toxaphene	1.1	0.32
Trichloroethylene	0.011	32.0

Source: Human Cancer Potencies from the Integrated Risks Information System (IRIS).
Reference Air Concentrations derived as discussed in Sections 5.3 and 5.4.

SECTION SIX

POLLUTANT LIMITS FOR SEWAGE SLUDGE PLACED ON A SURFACE DISPOSAL SITE

The Part 503 regulation pertaining to the surface disposal of sewage sludge contains pollutant limits for three pollutants—arsenic, chromium, and nickel. This section explains why EPA selected these three pollutants for regulation from the seventeen pollutants for which a risk assessment was conducted. It also describes how the concentration limits were established for the three pollutants.

6.1 POLLUTANT SELECTION PROCESS

Based on the results of the risk assessment for the surface disposal of sewage sludge (Section 5.5), EPA decided to delete from regulatory consideration those pollutants meeting one of the following three criteria:

- EPA has banned the pollutant for use in the United States; EPA has restricted the use of the pollutant in the United States; or the pollutant is neither manufactured nor used to manufacture a product in the United States.
- Based on the results of the National Sewage Sludge Survey, the pollutant has a low percentage of detection in sewage sludge.
- Based on data from the National Sewage Sludge Survey, the limit for an organic pollutant in the Part 503 risk assessment by use or disposal practice is not expected to be exceeded when sewage sludge is used or disposed.

For those pollutants meeting one of the above criteria, EPA believes, human health and the environment still are protected from the reasonably anticipated adverse effects of placing sewage sludge on a surface disposal site without establishing limits on those pollutants. Therefore, limits are not established under Part 503 for pollutants deleted on this basis (see Appendix E for additional discussion on the deletion of pollutants from the final Part 503

regulation). Table 6-1 lists the seven pollutants deleted from further regulatory consideration because they met two of the above criteria, while Table 6-2 lists seven additional pollutants deleted because they met one of the criteria. The three pollutants for which pollutant limits are established under Part 503, Subpart C, are listed in Table 6-3, along with the allowable pollutant concentration in sewage sludge that is placed on a surface disposal site.

6.2 DERIVATION OF POLLUTANT CONCENTRATION LIMITS

The established limit on the concentration of arsenic, chromium, and nickel in sewage sludge (other than domestic septage) placed on a surface disposal site depends on the distance between the boundary of the active sewage sludge unit and the property line of the site. For active sewage sludge units without a liner and leachate collection system whose boundary is less than 150 meters from the property line of the site, the pollutant concentration in the sewage sludge cannot exceed the limit established in Table 6-3. (See Appendix E for a discussion about why no pollutant limits are established for domestic septage.)

EPA derived the pollutant concentration limits in Table 6-3 by selecting either the lowest risk-based criteria value from four tables from Section Five (Table 5-6 to 5-9) or the pollutant concentration representing the 99th percentile of sewage sludge samples analyzed for the National Sewage Sludge Survey, whichever was more stringent. Tables 5-6 through 5-9 present the results of the risk assessment for sewage sludge placed in both a lined or unlined monofill and surface impoundment over Class II/III ground water. The risk assessment also developed pollutant criteria for placement of sewage sludge in a lined or unlined monofill and surface impoundment over Class I ground water. However, after additional consideration, EPA determined that it would be more appropriate to treat all ground water as drinkable in accordance with a Class II designation. For this reason, only the pollutant criteria developed for sewage sludge placed on a surface disposal site over Class II/III ground water was considered for the pollutant limits. All risk-based pollutant criteria were reported to two significant figures and rounded down. For example, a pollutant criterion of 113 mg/kg was rounded to 110 mg/kg.

TABLE 6-1

**POLLUTANTS DELETED FROM REGULATORY CONSIDERATION
FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE
(MEET TWO OF THREE DELETION CRITERIA)**

Pollutant	Reason Deleted
Benzo(a)pyrene	Met Criteria #1, 2 and 3
Chlordane	Met Criteria #1, 2 and 3
DDT/DDD/DDE	Met Criteria #1, 2 and 3
Lindane	Met Criteria #1, 2 and 3
n-Nitrosodimethylamine	Met Criteria #1 and 2
PCBs	Met Criteria #1 and 2
Toxaphene	Met Criteria #1, 2 and 3

TABLE 6-2

**POLLUTANTS DELETED FROM REGULATORY CONSIDERATION
FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE
(MEET ONE OF THREE DELETION CRITERIA)**

Pollutant	Reason Deleted
Benzene	Met Criterion #2
Bis (2-ethylhexyl) phthalate	Met Criterion #3
Cadmium	Met Criterion #3
Copper	Met Criterion #3
Lead	Met Criterion #3
Mercury	Met Criterion #3
Trichloroethylene	Met Criterion #2

TABLE 6-3

**POLLUTANTS REGULATED BY THE PART 503 REGULATION
FOR THE SURFACE DISPOSAL OF SEWAGE SLUDGE**

Pollutant	Concentration (mg/kg)*
Arsenic	73
Chromium	600
Nickel	420

*Dry weight basis

The risk assessment results presented in Tables 5-6 to 5-9 are summarized in Table 6-4. For arsenic and chromium, the pollutant limits established in Part 503, Subpart C, are the lowest risk-based criteria from the table. The nickel limit, however, is taken to be the 99th percentile value from the NSSS, since that value (420 mg/kg) is more stringent than the lowest risk-based criterion derived from the risk assessment (690 mg/kg).

Table 6-4 highlights two significant outcomes of the risk assessment. First, none of the pollutant limits is derived from the risk-based criteria developed through the vapor pathway, since all three pollutants are inorganic compounds that do not tend to volatilize. Second, none of the pollutant limits is derived from criteria developed through modeling a lined monofill or surface impoundment for the ground-water pathway, since all the calculated risk-based pollutant loading criteria for lined units are unlimited values. Because the risk assessment showed that risks to human health from the placement of sewage sludge in lined sewage sludge units with leachate collection systems were negligible, pollutant limits under Part 503 only apply to unlined sewage sludge units without leachate collection. Part 503 does, however, establish management practices for sites with a liner and leachate collection system, as well as those without liners and leachate collection systems (see Section Seven).

For active sewage sludge units without a liner and leachate collection system whose boundary is less than 150 meters from the property line of the site, the pollutant concentration in the sewage sludge cannot exceed that shown in Table 6-5. These limits were derived based on the same risk assessment models used to develop limits in Table 6-3. The difference between the model assumptions used is that, for Table 6-3, exposure is modeled for an HEI who is 150 meters from the sewage sludge unit, whereas for Table 6-5, the HEI is located a distance less than 150 meters from the unit. The owner/operator of the surface disposal site needs to determine the actual distance between the unit and the property line of the site to derive the pollutant concentration limits.

In addition to the pollutant concentration limits presented in Tables 6-3 and 6-5, an owner/operator of a surface disposal site can, at the time of permit application, request that the permitting authority develop site-specific limits, if appropriate, when the actual values for the site parameters are different from the generic values used in the risk assessment to develop the

TABLE 6-4

**SUMMARY OF RISK ASSESSMENT RESULTS FOR ARSENIC, CHROMIUM,
AND NICKEL FOR SEWAGE SLUDGE DISPOSAL IN A LINED OR
UNLINED MONOFILL AND SURFACE IMPOUNDMENT
OVER CLASS II/III GROUND WATER**

Contaminant	Ground-Water Pathway			Vapor Pathway		
	Unlined Monofill	Unlined Surface Impoundment	Lined Monofill	Lined Surface Impoundment	Unlined Monofill	Lined Surface Impoundment
nickel	140	73	unlimited	unlimited	NA	NA
chromium	unlimited	600	unlimited	unlimited	NA	NA
lead	unlimited	690	unlimited	unlimited	NA	NA

indicates that it was NOT APPLICABLE to conduct a risk assessment on these three pollutants for the vapor pathway since they do not tend to volatilize.

unlimited—indicates that the calculated risk-based pollutant loading criteria for those media and disposal practices were an unlimited value.

TABLE 6-5

**POLLUTANT CONCENTRATIONS FOR AN ACTIVE SEWAGE SLUDGE
UNIT WITHOUT A LINER AND LEACHATE COLLECTION
SYSTEM THAT HAS A UNIT BOUNDARY TO PROPERTY
LINE DISTANCE LESS THAN 150 METERS**

Unit Boundary to Property Line Distance (meters)	Pollutant Concentration*		
	Arsenic (mg/kg)	Chromium (mg/kg)	Nickel (mg/kg)
0 to less than 25	30	200	210
25 to less than 50	34	220	240
50 to less than 75	39	260	270
75 to less than 100	46	300	320
100 to less than 125	53	360	390
125 to less than 150	62	450	420

*Dry weight basis

pollutant limits in Table 6-3. The concentration of the three pollutants in sewage sludge placed in an active sewage sludge unit without a liner or leachate collection system cannot exceed either the concentration of the pollutant calculated based on site-specific parameters (as specified by the permitting authority) or the existing concentration of the pollutant in the sewage sludge being placed in the unit, whichever is lower.

SECTION SEVEN

MANAGEMENT PRACTICES

The Part 503 regulation, Subpart C, specifies management practices (Section 503.24) that must be met if sewage sludge is prepared for, or placed on, a surface disposal site. These management practices were established to ensure adequate protection of human health and the environment by specifying requirements not addressed by the pollutant limits set forth in the Part 503 regulation. These management practices are discussed below.

7.1 PROTECTION OF THREATENED OR ENDANGERED SPECIES

Sewage sludge must not be placed on an active sewage sludge unit if it is likely to adversely affect a threatened or endangered species listed under Section 4 of the Endangered Species Act or its designated critical habitat. EPA will develop guidance to carry out this provision consistent with the Endangered Species Act.

7.2 RESTRICTION OF BASE FLOOD FLOW

An active sewage sludge unit cannot restrict the flow of a base flood. This management practice reduces the potential for a surface disposal site to disrupt an area that carries a 100-year flood, limits the potential for sewage sludge to be swept up in surface water during a flood, and also protects the surface disposal site from impacts of a base flood.

7.3 GEOLOGICAL STABILITY

Three of the management practices in Subpart C involve the location of active sewage sludge units in relation to geologic formations. These management practices help ensure that

active sewage sludge units are located in geologically stable areas and that the units can tolerate certain ground movements. The intent of these management practices is to protect human health and the environment by preventing uncontrolled releases of pollutants in sewage sludge resulting from unstable geological conditions. The three types of management practices related to geological stability are discussed below.

7.3.1 Seismic Impact Zones

When a surface disposal site is located in a seismic impact zone, an active sewage sludge unit must be designed to withstand the maximum recorded horizontal ground-level acceleration. This management practice helps ensure that the containment structures (e.g., slopes, liner and leachate collection system) of an active sewage sludge unit will remain intact (e.g., will not crack or collapse) because of ground movement. Various seismic design methods are available to evaluate designs under seismic conditions (Lambe and Whitman, 1969; Hynes-Griffin and Franklin, 1984).

7.3.2 Fault Areas

An active sewage sludge unit must be located at least 60 meters from a fault that has displacement in Holocene time, unless otherwise specified by the permitting authority. This setback distance helps ensure that the structural integrity of an active sewage sludge unit will not be affected should geologic movement occur in a fault area. Guidelines are available for identifying fault areas (State of California, 1975).

7.3.3 Unstable Areas

An active sewage sludge unit cannot be located in an unstable area, such as areas prone to landslides; areas with expansive soils; or subsidence areas (areas where the land surface is lowered or has collapsed because of the dissolution of limestone or other soluble materials).

This management practice helps to protect the structural components of an active sewage sludge unit from damage by natural or human-induced forces. Owners/operators of surface disposal sites may need to perform local geotechnical studies to determine that unstable conditions do not exist at the site.

7.4 PROTECTION OF WETLANDS

Wetlands are known to provide important ecological functions such as holding flood waters, retaining pollutants, serving as sources for food and habitat for numerous species, reducing erosion, and acting as recharge areas for ground water (Office of Technology Assessment, 1984). An active sewage sludge unit cannot be located in a wetland, unless a permit was issued under Sections 402 or 404 of the Clean Water Act. The risk assessment performed to establish pollutant limits in Subpart C did not address wetlands protection. This management practice provides wetlands protection from possible contamination from pollutants in sewage sludge.

7.5 COLLECTION OF RUNOFF

Runoff from an active sewage sludge unit must be collected and disposed according to the National Pollutant Discharge Elimination System and any other applicable requirements. In addition, the runoff collection system of an active sewage sludge unit must have the capacity to handle runoff from a 24-hour, 25-year storm event. The risk assessment for the Part 503 regulation and the pollutant limits do not evaluate risk from exposure to contaminated surface water because these management practices controlling runoff are assumed to be in place.

7.6 COLLECTION OF LEACHATE

Leachate is fluid generated from excess moisture in the sewage sludge or from water percolating through the site. Depending on the nature of the waste, leachate may contain

metals, nutrients, and toxic organic chemicals. Two management practices in Subpart C address collection of leachate from active sewage sludge units that have a liner and leachate collection system. The first management practice requires that the leachate collection system be operated and maintained while the unit is active and for three years after the unit closes. The second management practice requires that leachate be collected and disposed in accordance with applicable requirements while the unit is active and for three years after the unit closes. These management practices seek to ensure that the liner is not damaged (e.g., by hydraulic pressure from the leachate) and that pollutants in sewage sludge are prevented from being released into the environment. This management practice regulates only active sewage sludge units *with* a liner and leachate collection system. The Part 503 rule regulates active sewage sludge units *without* liners and leachate collection systems through the pollutant limits in Section 503.23 and through other requirements in the regulation.

7.7 LIMITATIONS ON METHANE GAS CONCENTRATIONS

The final Part 503 regulation contains a management practice that limits concentrations of methane gas because of its explosive potential. Methane gas is generated and released from a sewage sludge unit when the sewage sludge is covered (because of anaerobic conditions). This management practice requires that:

- If a cover is placed on an active sewage sludge unit, the concentration of methane gas in air in any structure within the surface disposal site cannot exceed 25 percent of the lower explosive limit for methane gas, and the concentration of methane gas in the air at the property line of the surface disposal site cannot exceed the lower explosive limit during the period that the sewage sludge unit is active.
- If a final cover is placed on a sewage sludge unit at closure, the concentration of methane gas in air in any structure within the surface disposal site cannot exceed 25 percent of the lower explosive limit, and the concentration of methane gas in the air at the property line of the surface disposal site cannot exceed the lower explosive limit for 3 years after the sewage sludge unit closes, unless otherwise specified by the permitting authority.

Twenty-five percent of the lower explosive limit is the level used by other Federal regulations, such as Occupational Safety and Health and National Fire Protection Code regulations. Since the human health standard for methane is greater than the lower explosive level, the EPA believes that the limits set forth in this management practice provide an adequate margin of safety to protect human health and the environment. Various methods are available to control methane gas (U.S. EPA, 1977; Raymond Vail and Assoc., 1979).

7.8 PROHIBITION ON CROP PRODUCTION

Food, feed, or fiber crops cannot be grown on an active sewage sludge unit unless the owner or operator of the surface disposal site can demonstrate to the permitting authority that public health and the environment are protected, through management practices, from reasonably anticipated adverse effects of pollutants in the sewage sludge when crops are grown. This management practice is included because the risk assessment for the final Part 503 regulation and the pollutant limits in the regulation do not address crop production on active sewage sludge units.

7.9 PROHIBITION ON GRAZING

Animals cannot be allowed to graze on an active sewage sludge unit unless the owner/operator of the surface disposal site can demonstrate to the permitting authority that public health and the environment are protected, through management practices, from reasonably anticipated adverse effects of pollutants in sewage sludge when animals are grazed (e.g., through ingestion of the sewage sludge/soil mixture). This management practice is included because the risk assessment for the final Part 503 regulation and the pollutant limits in the regulation do not address grazing of animals on active sewage sludge units.

7.10 RESTRICTION OF PUBLIC ACCESS

Public access to a surface disposal site must be restricted while the site contains an active sewage sludge unit and for three years after the last active sewage sludge unit in the surface disposal site closes. This management practice is included because the risk assessment for the final Part 503 regulation and the pollutant limits in the regulation do not address the potential for public contact with sewage sludge placed on an active sewage sludge unit (e.g., ingestion of sewage sludge/soil, methane gas explosions).

7.11 PROTECTION OF GROUND WATER

This management practice states that sewage sludge placed on an active sewage sludge unit cannot contaminate an aquifer. This must be confirmed by the results of a ground-water monitoring program developed by a qualified ground-water scientist or by certification by a ground-water scientist. This management practice is included because the pollutant limits established in Subpart C for surface disposal do not address potential nitrate contamination of ground water, which can result from leachate percolating through the soil.

SECTION EIGHT

PATHOGEN AND VECTOR ATTRACTION REDUCTION REQUIREMENTS

Subpart C specifies operational standards (Section 503.25) to control pathogen levels and reduce the attraction of vectors (e.g., insects, rodents) in sewage sludge and domestic septage placed on an active sewage sludge unit. Operational standards are set when, in the judgment of the EPA Administrator, they fulfill regulatory requirements to protect human health and the environment from reasonably anticipated adverse effects. The operational standards in Subpart C refer to specific requirements in Part 503, Subpart D, entitled Pathogens and Vector Attraction Reduction (Sections 503.32 and 503.33). Pathogen and vector attraction reduction requirements as they apply to surface disposal of sewage sludge are discussed below. For detailed information on these requirements, see Subpart D of the Part 503 regulation and the *Technical Support Document for Part 503 Pathogen and Vector Attraction Reduction Requirements* (U.S. EPA, 1992b).

8.1 PATHOGEN REQUIREMENTS

Sewage sludge, other than domestic septage, placed on an active sewage sludge unit must meet either the Class A or Class B pathogen requirements (except site restrictions under Class B requirements) specified in Subpart D (Section 503.32), unless a cover is placed on the active sewage sludge unit at the end of each operating day. Class A pathogen requirements are more stringent than Class B requirements and can be met by testing the sewage sludge for certain pathogens of concern. If necessary, Class A requirements can also be met by treating the sewage sludge with one of the Processes to Further Reduce Pathogens (PFRP) or by other methods described in Subpart D. Class B pathogen requirements can be met by testing the sewage sludge for certain pathogens of concern and, if necessary, treating the sewage sludge with one of the Processes to Significantly Reduce Pathogens (PSRP) or by other methods described in Subpart D.

As mentioned above, if a daily cover is used on an active sewage sludge unit, the pathogen requirements do not have to be met because a daily cover isolates the sewage sludge and reduces pathogen formation in sewage sludge. Site restrictions specified in Subpart D for sewage sludge meeting Class B pathogen requirements do not need to be met for sewage sludge placed on surface disposal sites because the management practices specified in Subpart C (see Section Seven) already impose these site restrictions (e.g., restrictions on crop production, animal grazing, and public contact). Similarly, domestic septage placed on an active sewage sludge unit does not have to meet the pathogen requirements of Subpart D because the management practices in Subpart C already impose site restrictions on crop production, animal grazing, and public contact for active sewage sludge units and because 40 CFR Part 257 already requires that domestic septage applied to land on which food crops are grown be treated in a Process to Significantly Reduce Pathogens (PSRP).

8.2 VECTOR ATTRACTION REDUCTION

Subpart D (Section 503.33) specifies vector attraction reduction requirements for sewage sludge, including domestic septage, placed on an active sewage sludge unit. For sewage sludge other than domestic septage, one of several vector attraction reduction requirements outlined in Subpart D must be met, including using a daily cover to prevent access to sewage sludge by vectors; reducing volatile solids content; meeting a specific oxygen uptake rate (SOUR); treating the sewage sludge in an aerobic process; raising the pH of the sewage sludge for a specified time; meeting a minimum percent solids content; or injecting or incorporating sewage sludge into the soil. These practices must be conducted according to the requirements specified in Subpart D.

For domestic septage, vector attraction reduction requirements must be met by employing one of the following practices: placing a daily cover on an active sewage sludge unit; injecting or incorporating the domestic septage into the soil; or raising the pH of the domestic septage for a specified time that is less than that required for other types of sewage sludge. These practices must be conducted according to the requirements specified in Subpart D.

SECTION NINE

FREQUENCY OF MONITORING, RECORDKEEPING, AND REPORTING REQUIREMENTS

The Part 503 regulation specifies monitoring, recordkeeping, and reporting requirements for sewage sludge, including domestic septage, placed on a surface disposal site. These requirements are discussed below.

9.1 FREQUENCY OF MONITORING

The Part 503 regulation requires that sewage sludge placed on an active sewage sludge unit be monitored for regulated pollutant concentrations (arsenic, chromium, and nickel), pathogen requirements, and vector attraction reduction requirements. Domestic septage must be monitored for pH under certain conditions. In addition, air at a surface disposal site must be monitored for methane gas. These requirements are discussed in more detail below.

9.1.1 Sewage Sludge (Other Than Domestic Septage)

Sewage sludge other than domestic septage placed on an active sewage sludge unit must be monitored for arsenic, chromium, and nickel; pathogen requirements (in Section 503.32(a) or 503.32(b) of the Part 503 regulation); and the applicable vector attraction reduction requirement (Section 503.33(b)).

The minimum frequency of monitoring required by the regulation is based on the amount of sewage sludge placed on an active sewage sludge unit annually and ranges from once per year to once per month, as shown in Table 9-1. The calculations used to develop the different amounts of sewage sludge on which the monitoring frequency is based are shown in Appendix F.

TABLE 9-1

**MINIMUM FREQUENCY OF MONITORING
FOR SURFACE DISPOSAL OF SEWAGE SLUDGE**

Amounts of Sewage Sludge* (Metric Tons per 365-Day Period)	Minimum Frequency
Greater than zero but less than 290	Once per year
Equal to or greater than 290 but less than 1,500	Once per quarter (four times per year)
Equal to or greater than 1,500 but less than 15,000	Once per 60 days (six times per year)
Equal to or greater than 15,000	Once per month (twelve times per year)

*Amount of sewage sludge (other than domestic septage) placed on an active sewage sludge unit
— dry weight basis.

After the sewage sludge has been monitored for two years at the frequency specified in Table 9-1, the permitting authority may reduce the frequency of monitoring for arsenic, chromium, and nickel, and for the pathogen requirements (which involve an analysis of sewage sludge prior to treating it for pathogens to determine whether the sewage sludge contains enteric viruses or viable helminth ova—see Appendix A, Subpart D). The frequency of monitoring cannot, however, be less than once per year if sewage sludge is placed on an active sewage sludge unit.

9.1.2 Domestic Septage

If the vector attraction reduction requirement is met by raising the pH of domestic septage as specified in Subpart D (Section 503.33(b)(12)), then each container of domestic septage placed on an active sewage sludge unit must be monitored for pH to ensure compliance.

9.1.3 Air Monitoring for Methane Gas

The Part 503 regulation also requires that air at a surface disposal site be monitored continuously for methane gas. Air monitoring must be performed at the property line of the surface disposal site and in all structures within a surface disposal site. Monitoring must occur while the site contains an active sewage sludge unit that is covered and for three years after a sewage sludge unit closes when a final cover is placed on the sewage sludge. (See also Section 7.7.)

9.2 RECORDKEEPING

The Part 503 regulation requires that certain information be recorded and retained for 5 years whenever sewage sludge is placed on a surface disposal site. Different recordkeeping requirements apply to: (a) a person who prepares sewage sludge for placement on an active sewage sludge unit, and (b) the owner/operator of a surface disposal site. These records must be kept whether or not a permit is required for certain activities. Different requirements exist for domestic septage than for other types of sewage sludge. The recordkeeping requirements in the Part 503 regulation are discussed below.

9.2.1 Sewage Sludge (Other Than Domestic Septage)

A person who prepares sewage sludge (other than domestic septage) for placement on an active sewage sludge unit must develop and retain the following information for 5 years:

- The concentrations of arsenic, chromium, and nickel in sewage sludge meeting the pollutant limits specified in Table 1 of Part 503.23.
- A certification statement, as worded in Part 503.27(a)(1)(ii) (see Appendix A).
- A description of how certain pathogen and vector attraction reduction requirements in Subpart D are met.

An owner/operator of the surface disposal site on which sewage sludge (other than domestic septage) is placed must develop and retain the following information for 5 years:

- The concentrations of arsenic, chromium, and nickel in sewage sludge meeting the pollutant limits in Table 2 or site-specific pollutant limits as specified in Part 503.23.
- A certification statement, as worded in Part 503.27(a)(2)(ii) (see Appendix A).
- A description of how the management practices in Subpart C are met.
- A description of how certain vector attraction reduction requirements in Subpart D are met.

9.2.2 Domestic Septage

A person who prepares domestic septage for placement on an active sewage sludge unit must develop and retain the following information for 5 years when the vector attraction reduction requirement is met by raising the pH of the domestic septage as specified in Subpart D, 503.33(b)(12):

- A certification statement, as worded in Part 503.27(b)(1)(i) (see Appendix A).
- A description of how the vector attraction reduction requirement in 503.33(b)(12) (raising the pH of domestic septage) is met.

An owner/operator of a surface disposal site on which domestic septage is placed must develop and retain the following information for 5 years:

- A certification statement, as worded in Part 503.27(b)(2)(i) (see Appendix A).
- A description of how the management practices in Subpart C are met.
- A description of how certain vector attraction reduction requirements in Subpart D are met.

9.3 REPORTING REQUIREMENTS

The Part 503 regulation specifies reporting requirements only for the following types of facilities:

- Class I sludge management facilities.
- Publicly owned treatment works (POTWs) with a design flow rate equal to or greater than 1 MGD.
- POTWs that serve 10,000 people or more.

These facilities must submit the information (except for data on domestic septage) they developed in 503.27(a) (described above) annually to the permitting authority.

SECTION TEN

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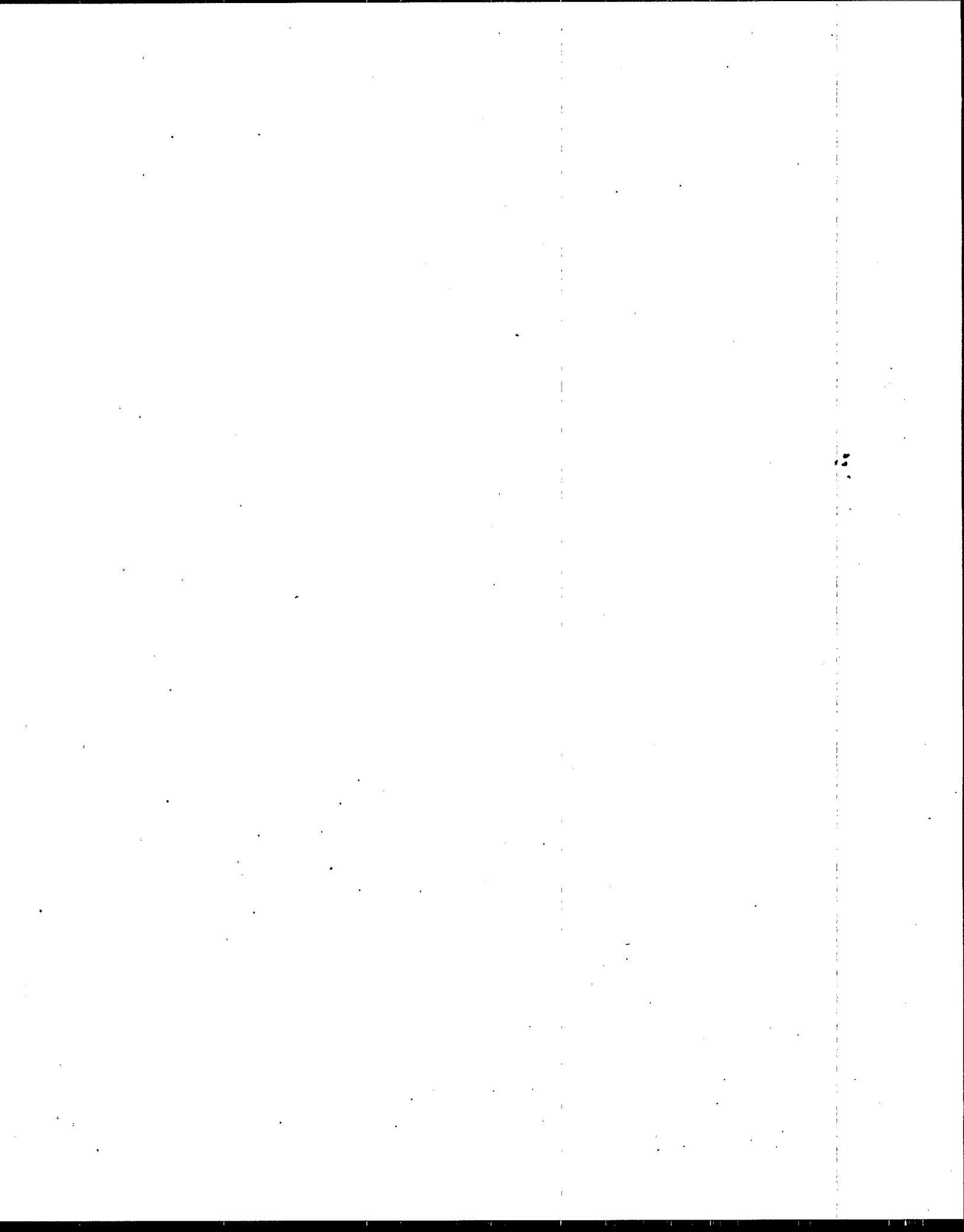
APPENDIX A

STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE

Subpart A—General Provisions

Subpart C—Surface Disposal

Subpart D—Pathogens and Vector Attraction Reduction



Pollutant	Use or disposal practice			
	LA	(SD)		I
		Unlined ¹	Lined ²	
Chromium				
Copper			³ 100	
DDD, DDE, DDT (Total)		³ 45	³ 100	1400
2,4 Dichlorophenoxy-acetic acid	1.2	2000	2000	
Fluoride		7	7	
Heptachlor	730			
Hexachlorobenzene	7.4			
Hexachlorobutadiene	29			
Iron	600			
Lead	³ 78			
Lindane		³ 100	³ 100	
Malathion	84	³ 28	³ 28	
Mercury		0.63	0.63	
Molybdenum		³ 100	³ 100	
Nickel		40	40	
N-Nitrosodimethylamine			³ 100	
Pentachlorophenol	2.1	0.088	0.088	
Phenol	30			
Polychlorinated biphenyls		82	82	
Selenium	4.6	<50	<50	
Toxaphene		4.8	4.8	4.8
Trichloroethylene	10	³ 26	³ 26	
Zinc	³ 10	9500	³ 10	
		4500	4500	4500

Key: LA—land application, SD—surface disposal, I—incineration.

¹ Sewage sludge unit without a liner and leachate collection system.

² Sewage sludge unit with a liner and leachate collection system.

³ Value expressed in grams per kilogram—dry weight basis.

Subchapter O in chapter I of title 40 of the Code of Federal Regulations is amended by adding part 503, which reads as follows:

SUBCHAPTER O—SEWAGE SLUDGE.

PART 503—STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE

Subpart A—General Provisions

Sec.

- 503.1 Purpose and applicability.
- 503.2 Compliance period.
- 503.3 Permits and direct enforceability
- 503.4 Relationship to other regulations.
- 503.5 Additional or more stringent requirements.
- 503.6 Exclusions.
- 503.7 Requirement for a person who prepares sewage sludge.
- 503.8 Sampling and analysis.
- 503.9 General definitions.

Subpart B—Land Application

- 503.10 Applicability.
- 503.11 Special definitions.
- 503.12 General requirements.
- 503.13 Pollutant limits.
- 503.14 Management practices.
- 503.15 Operational standards—pathogens and vector attraction reduction.
- 503.16 Frequency of monitoring.
- 503.17 Recordkeeping.
- 503.18 Reporting.

Subpart C—Surface Disposal

- 503.20 Applicability.
- 503.21 Special definitions.
- 503.22 General requirements.
- 503.23 Pollutant limits (other than domestic septage).
- 503.24 Management practices.

- 503.25 Operational standards—pathogens and vector attraction reduction.
- 503.26 Frequency of monitoring.
- 503.27 Recordkeeping.
- 503.28 Reporting.

Subpart D—Pathogens and Vector Attraction Reduction

- 503.30 Scope.
- 503.31 Special definitions.
- 503.32 Pathogens.
- 503.33 Vector attraction reduction.

Subpart E—Incineration

- 503.40 Applicability.
- 503.41 Special definitions.
- 503.42 General requirements.
- 503.43 Pollutant limits.
- 503.44 Operational standard—total hydrocarbons.
- 503.45 Management practices.
- 503.46 Frequency of monitoring.
- 503.47 Recordkeeping.
- 503.48 Reporting.

Appendix A to Part 503—Procedure to Determine the Annual Whole Sludge Application Rate for a Sewage Sludge

Appendix B to Part 503—Pathogen Treatment Processes

Authority: Sections 405 (d) and (e) of the Clean Water Act, as amended by Pub. L. 95-217, Sec. 54(d), 91 Stat. 1591 (33 U.S.C. 1345 (d) and (e)); and Pub. L. 100-4, Title IV, Sec. 406 (a), (b), 101 Stat., 71, 72 (33 U.S.C. 1251 et seq.).

Subpart A—General Provisions

§ 503.1 Purpose and applicability.

(a) *Purpose.* (1) This part establishes standards, which consist of general

requirements, pollutant limits, management practices, and operational standards, for the final use or disposal of sewage sludge generated during the treatment of domestic sewage in a treatment works. Standards are included in this part for sewage sludge applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator. Also included in this part are pathogen and alternative vector attraction reduction requirements for sewage sludge applied to the land or placed on a surface disposal site.

(2) In addition, the standards in this part include the frequency of monitoring and recordkeeping requirements when sewage sludge is applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator. Also included in this part are reporting requirements for Class I sludge management facilities, publicly owned treatment works (POTWs) with a design flow rate equal to or greater than one million gallons per day, and POTWs that serve 10,000 people or more.

(b) *Applicability.* (1) This part applies to any person who prepares sewage sludge, applies sewage sludge to the land, or fires sewage sludge in a sewage sludge incinerator and to the owner/operator of a surface disposal site.

(2) This part applies to sewage sludge applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator.

(3) This part applies to the exit gas from a sewage sludge incinerator stack.

(4) This part applies to land where sewage sludge is applied, to a surface disposal site, and to a sewage sludge incinerator.

§ 503.2 Compliance period.

(a) Compliance with the standards in this part shall be achieved as expeditiously as practicable, but in no case later than February 19, 1994. When compliance with the standards requires construction of new pollution control facilities, compliance with the standards shall be achieved as expeditiously as practicable, but in no case later than February 19, 1995.

(b) The requirements for frequency of monitoring, recordkeeping, and reporting in this part for total hydrocarbons in the exit gas from a sewage sludge incinerator are effective February 19, 1994 or, if compliance with the operational standard for total hydrocarbons in this part requires the construction of new pollution control facilities, February 19, 1995.

(c) All other requirements for frequency of monitoring, recordkeeping, and reporting in this part are effective on July 20, 1993.

§ 503.3 Permits and direct enforceability.

(a) Permits. The requirements in this part may be implemented through a permit:

(1) Issued to a "treatment works treating domestic sewage", as defined in 40 CFR 122.2, in accordance with 40 CFR parts 122 and 124 by EPA or by a State that has a State sludge management program approved by EPA in accordance with 40 CFR part 123 or 40 CFR part 501 or

(2) Issued under subtitle C of the Solid Waste Disposal Act; part C of the Safe Drinking Water Act; the Marine Protection, Research, and Sanctuaries Act of 1972; or the Clean Air Act. "Treatment works treating domestic sewage" shall submit a permit application in accordance with either 40 CFR 122.21 or an approved State program.

(b) Direct enforceability. No person shall use or dispose of sewage sludge through any practice for which requirements are established in this part except in accordance with such requirements.

§ 503.4 Relationship to other regulations.

Disposal of sewage sludge in a municipal solid waste landfill unit, as defined in 40 CFR 258.2, that complies with the requirements in 40 CFR part 258 constitutes compliance with section 405(d) of the CWA. Any person who prepares sewage sludge that is disposed in a municipal solid waste landfill unit

shall ensure that the sewage sludge meets the requirements in 40 CFR part 258 concerning the quality of materials disposed in a municipal solid waste landfill unit.

§ 503.5 Additional or more stringent requirements.

(a) On a case-by-case basis, the permitting authority may impose requirements for the use or disposal of sewage sludge in addition to or more stringent than the requirements in this part when necessary to protect public health and the environment from any adverse effect of a pollutant in the sewage sludge.

(b) Nothing in this part precludes a State or political subdivision thereof or interstate agency from imposing requirements for the use or disposal of sewage sludge more stringent than the requirements in this part or from imposing additional requirements for the use or disposal of sewage sludge.

§ 503.6 Exclusions.

(a) *Treatment processes.* This part does not establish requirements for processes used to treat domestic sewage or for processes used to treat sewage sludge prior to final use or disposal, except as provided in § 503.32 and § 503.33.

(b) *Selection of a use or disposal practice.* This part does not require the selection of a sewage sludge use or disposal practice. The determination of the manner in which sewage sludge is used or disposed is a local determination.

(c) *Co-firing of sewage sludge.* This part does not establish requirements for sewage sludge co-fired in an incinerator with other wastes or for the incinerator in which sewage sludge and other wastes are co-fired. Other wastes do not include auxiliary fuel, as defined in 40 CFR 503.41(b), fired in a sewage sludge incinerator.

(d) *Sludge generated at an industrial facility.* This part does not establish requirements for the use or disposal of sludge generated at an industrial facility during the treatment of industrial wastewater, including sewage sludge generated during the treatment of industrial wastewater combined with domestic sewage.

(e) *Hazardous sewage sludge.* This part does not establish requirements for the use or disposal of sewage sludge determined to be hazardous in accordance with 40 CFR part 261.

(f) *Sewage sludge with high PCB concentration.* This part does not establish requirements for the use or disposal of sewage sludge with a concentration of polychlorinated

biphenyls (PCBs) equal to or greater than 50 milligrams per kilogram of total solids (dry weight basis).

(g) *Incinerator ash.* This part does not establish requirements for the use or disposal of ash generated during the firing of sewage sludge in a sewage sludge incinerator.

(h) *Grit and screenings.* This part does not establish requirements for the use or disposal of grit (e.g., sand, gravel, cinders, or other materials with a high specific gravity) or screenings (e.g., relatively large materials such as rags) generated during preliminary treatment of domestic sewage in a treatment works.

(i) *Drinking water treatment sludge.* This part does not establish requirements for the use or disposal of sludge generated during the treatment of either surface water or ground water used for drinking water.

(j) *Commercial and industrial septage.* This part does not establish requirements for the use or disposal of commercial septage, industrial septage, a mixture of domestic septage and commercial septage, or a mixture of domestic septage and industrial septage.

§ 503.7 Requirement for a person who prepares sewage sludge.

Any person who prepares sewage sludge shall ensure that the applicable requirements in this part are met when the sewage sludge is applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator.

§ 503.8 Sampling and analysis.

(a) *Sampling.* Representative samples of sewage sludge that is applied to the land, placed on a surface disposal site, or fired in a sewage sludge incinerator shall be collected and analyzed.

(b) *Methods.* The materials listed below are incorporated by reference in this part. These incorporations by reference were approved by the Director of the Federal Register in accordance with 5 U.S.C. 552(a) and 1 CFR part 51. The materials are incorporated as they exist on the date of approval, and notice of any change in these materials will be published in the Federal Register. They are available for inspection at the Office of the Federal Register, 7th Floor, suite 700, 800 North Capitol Street, NW., Washington, DC, and at the Office of Water Docket, room L-102, U.S. Environmental Protection Agency, 401 M Street, SW., Washington, DC. Copies may be obtained from the standard producer or publisher listed in the regulation. Methods in the materials listed below shall be used to analyze samples of sewage sludge.

(1) *Enteric viruses*. ASTM Designation: D 4994-89, "Standard Practice for Recovery of Viruses From Wastewater Sludges", 1992 Annual Book of ASTM Standards: Section 11—Water and Environmental Technology, ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.

(2) *Fecal coliform*. Part 9221 E. or Part 9222 D., "Standard Methods for the Examination of Water and Wastewater", 18th Edition, 1992, American Public Health Association, 1015 15th Street, NW., Washington, DC 20005.

(3) *Helminth ova*. Yanko, W.A., "Occurrence of Pathogens in Distribution and Marketing Municipal Sludges", EPA 600/1-87-014, 1987. National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 (PB 88-154273/AS).

(4) *Inorganic pollutants*. "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods", EPA Publication SW-846, Second Edition (1982) with Updates I (April 1984) and II (April 1985) and Third Edition (November 1986) with Revision I (December 1987). Second Edition and Updates I and II are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 (PB-87-120-291). Third Edition and Revision I are available from Superintendent of Documents, Government Printing Office, 941 North Capitol Street, NE., Washington, DC 20002 (Document Number 955-001-00000-1).

(5) *Salmonella*.sp. *bacteria*. Part 9260 D., "Standard Methods for the Examination of Water and Wastewater", 18th Edition, 1992, American Public Health Association, 1015 15th Street, NW., Washington, DC 20005; or

Kenner, B.A. and H.P. Clark, "Detection and enumeration of *Salmonella* and *Pseudomonas aeruginosa*", Journal of the Water Pollution Control Federation, Vol. 46, no. 9, September 1974, pp. 2163-2171. Water Environment Federation, 601 Wythe Street, Alexandria, Virginia 22314.

(6) *Specific oxygen uptake rate*. Part 2710 B., "Standard Methods for the Examination of Water and Wastewater", 18th Edition, 1992, American Public Health Association, 1015 15th Street, NW., Washington, DC 20005.

(7) *Total, fixed, and volatile solids*. Part 2540 G., "Standard Methods for the Examination of Water and Wastewater", 18th Edition, 1992, American Public Health Association, 1015 15th Street, NW., Washington, DC 20005.

§ 503.9 General definitions.

(a) *Apply sewage sludge or sewage sludge applied to the land* means land application of sewage sludge.

(b) *Base flood* is a flood that has a one percent chance of occurring in any given year (i.e., a flood with a magnitude equalled once in 100 years).

(c) *Class I sludge management facility* is any publicly owned treatment works (POTW), as defined in 40 CFR 501.2, required to have an approved pretreatment program under 40 CFR 403.8(a) (including any POTW located in a State that has elected to assume local program responsibilities pursuant to 40 CFR 403.10(e)) and any treatment works treating domestic sewage, as defined in 40 CFR 122.2, classified as a Class I sludge management facility by the EPA Regional Administrator, or, in the case of approved State programs, the Regional Administrator in conjunction with the State Director, because of the potential for its sewage sludge use or disposal practice to affect public health and the environment adversely.

(d) *Cover crop* is a small grain crop, such as oats, wheat, or barley, not grown for harvest.

(e) *CWA* means the Clean Water Act (formerly referred to as either the Federal Water Pollution Act or the Federal Water Pollution Control Act Amendments of 1972), Public Law 92-500, as amended by Public Law 95-217, Public Law 95-576, Public Law 96-483, Public Law 97-117, and Public Law 100-4.

(f) *Domestic septage* is either liquid or solid material removed from a septic tank, cesspool, portable toilet, Type III marine sanitation device, or similar treatment works that receives only domestic sewage. Domestic septage does not include liquid or solid material removed from a septic tank, cesspool, or similar treatment works that receives either commercial wastewater or industrial wastewater and does not include grease removed from a grease trap at a restaurant.

(g) *Domestic sewage* is waste and wastewater from humans or household operations that is discharged to or otherwise enters a treatment works.

(h) *Dry weight basis* means calculated on the basis of having been dried at 105 degrees Celsius until reaching a constant mass (i.e., essentially 100 percent solids content).

(i) *EPA* means the United States Environmental Protection Agency.

(j) *Feed crops* are crops produced primarily for consumption by animals.

(k) *Fiber crops* are crops such as flax and cotton.

(l) *Food crops* are crops consumed by humans. These include, but are not

limited to, fruits, vegetables, and tobacco.

(m) *Ground water* is water below the land surface in the saturated zone.

(n) *Industrial wastewater* is wastewater generated in a commercial or industrial process.

(o) *Municipality* means a city, town, borough, county, parish, district, association, or other public body (including an intermunicipal Agency of two or more of the foregoing entities) created by or under State law; an Indian tribe or an authorized Indian tribal organization having jurisdiction over sewage sludge management; or a designated and approved management Agency under section 208 of the CWA, as amended. The definition includes a special district created under State law, such as a water district, sewer district, sanitary district, utility district, drainage district, or similar entity, or an integrated waste management facility as defined in section 201(e) of the CWA, as amended, that has as one of its principal responsibilities the treatment, transport, use, or disposal of sewage sludge.

(p) *Permitting authority* is either EPA or a State with an EPA-approved sludge management program.

(q) *Person* is an individual, association, partnership, corporation, municipality, State or Federal agency, or an agent or employee thereof.

(r) *Person who prepares sewage sludge* is either the person who generates sewage sludge during the treatment of domestic sewage in a treatment works or the person who derives a material from sewage sludge.

(s) *Place sewage sludge or sewage sludge placed* means disposal of sewage sludge on a surface disposal site.

(t) *Pollutant* is an organic substance, an inorganic substance, a combination of organic and inorganic substances, or a pathogenic organism that, after discharge and upon exposure, ingestion, inhalation, or assimilation into an organism either directly from the environment or indirectly by ingestion through the food chain, could, on the basis of information available to the Administrator of EPA, cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunction in reproduction), or physical deformations in either organisms or offspring of the organisms.

(u) *Pollutant limit* is a numerical value that describes the amount of a pollutant allowed per unit amount of sewage sludge (e.g., milligrams per kilogram of total solids); the amount of a pollutant that can be applied to a unit area of land (e.g., kilograms per hectare); or the volume of a material that can be

applied to a unit area of land (e.g., gallons per acre).

(v) *Runoff* is rainwater, leachate, or other liquid that drains overland on any part of a land surface and runs off of the land surface.

(w) *Sewage sludge* is solid, semi-solid, or liquid residue generated during the treatment of domestic sewage in a treatment works. Sewage sludge includes, but is not limited to, domestic septage; scum or solids removed in primary, secondary, or advanced wastewater treatment processes; and a material derived from sewage sludge. Sewage sludge does not include ash generated during the firing of sewage sludge in a sewage sludge incinerator or grit and screenings generated during preliminary treatment of domestic sewage in a treatment works.

(x) *State* is one of the United States of America, the District of Columbia, the Commonwealth of Puerto Rico, the Virgin Islands, Guam, American Samoa, the Trust Territory of the Pacific Islands, the Commonwealth of the Northern Mariana Islands, and an Indian Tribe eligible for treatment as a State pursuant to regulations promulgated under the authority of section 518(e) of the CWA.

(y) *Store or storage of sewage sludge* is the placement of sewage sludge on land on which the sewage sludge remains for two years or less. This does not include the placement of sewage sludge on land for treatment.

(z) *Treat or treatment of sewage sludge* is the preparation of sewage sludge for final use or disposal. This includes, but is not limited to, thickening, stabilization, and dewatering of sewage sludge. This does not include storage of sewage sludge.

(aa) *Treatment works* is either a federally owned, publicly owned, or privately owned device or system used to treat (including recycle and reclaim) either domestic sewage or a combination of domestic sewage and industrial waste of a liquid nature.

(bb) *Wetlands* means those areas that are inundated or saturated by surface water or ground water at a frequency and duration to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.

Subpart B—Land Application

§ 503.10 Applicability.

(a) This subpart applies to any person who prepares sewage sludge that is applied to the land, to any person who applies sewage sludge to the land, to

sewage sludge applied to the land, and to the land on which sewage sludge is applied.

(b)(1) *Bulk sewage sludge*. The general requirements in § 503.12 and the management practices in § 503.14 do not apply when bulk sewage sludge is applied to the land if the bulk sewage sludge meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

(2) The Regional Administrator of EPA or, in the case of a State with an approved sludge management program, the State Director, may apply any or all of the general requirements in § 503.12 and the management practices in § 503.14 to the bulk sewage sludge in § 503.10(b)(1) on a case-by-case basis after determining that the general requirements or management practices are needed to protect public health and the environment from any reasonably anticipated adverse effect that may occur from any pollutant in the bulk sewage sludge.

(c)(1) The general requirements in § 503.12 and the management practices in § 503.14 do not apply when a bulk material derived from sewage sludge is applied to the land if the derived bulk material meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

(2) The Regional Administrator of EPA or, in the case of a State with an approved sludge management program, the State Director, may apply any or all of the general requirements in § 503.12 or the management practices in § 503.14 to the bulk material in § 503.10(c)(1) on a case-by-case basis after determining that the general requirements or management practices are needed to protect public health and the environment from any reasonably anticipated adverse effect that may occur from any pollutant in the bulk sewage sludge.

(d) The requirements in this subpart do not apply when a bulk material derived from sewage sludge is applied to the land if the sewage sludge from which the bulk material is derived meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

(e) *Sewage sludge sold or given away in a bag or other container for application to the land*. The general

requirements in § 503.12 and the management practices in § 503.14 do not apply when sewage sludge is sold or given away in a bag or other container for application to the land if the sewage sludge sold or given away in a bag or other container for application to the land meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

(f) The general requirements in § 503.12 and the management practices in § 503.14 do not apply when a material derived from sewage sludge is sold or given away in a bag or other container for application to the land if the derived material meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

(g) The requirements in this subpart do not apply when a material derived from sewage sludge is sold or given away in a bag or other container for application to the land if the sewage sludge from which the material is derived meets the pollutant concentrations in § 503.13(b)(3), the Class A pathogen requirements in § 503.32(a), and one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8).

§ 503.11 Special definitions.

(a) *Agricultural land* is land on which a food crop, a feed crop, or a fiber crop is grown. This includes range land and land used as pasture.

(b) *Agronomic rate* is the whole sludge application rate (dry weight basis) designed:

(1) To provide the amount of nitrogen needed by the food crop, feed crop, fiber crop, cover crop, or vegetation grown on the land; and

(2) To minimize the amount of nitrogen in the sewage sludge that passes below the root zone of the crop or vegetation grown on the land to the ground water.

(c) *Annual pollutant loading rate* is the maximum amount of a pollutant that can be applied to a unit area of land during a 365 day period.

(d) *Annual whole sludge application rate* is the maximum amount of sewage sludge (dry weight basis) that can be applied to a unit area of land during a 365 day period.

(e) *Bulk sewage sludge* is sewage sludge that is not sold or given away in a bag or other container for application to the land.

other container for application to the land, the person who prepares the sewage sludge that is sold or given away in a bag or other container shall develop the following information and shall retain the information for five years:

(i) The annual whole sludge application rate for the sewage sludge that does not cause the annual pollutant loading rates in Table 4 of § 503.13 to be exceeded.

(ii) The concentration of each pollutant listed in Table 4 of § 503.13 in the sewage sludge.

(iii) The following certification statement:

"I certify, under penalty of law, that the management practice in § 503.14(e), the Class A pathogen requirement in § 503.32(a), and the vector attraction reduction requirement in [insert one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8)] have been met. This determination has been made under my direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine that the management practice, pathogen requirements, and vector attraction reduction requirements have been met. I am aware that there are significant penalties for false certification including the possibility of fine and imprisonment."

(iv) A description of how the Class A pathogen requirements in § 503.32(a) are met.

(v) A description of how one of the vector attraction requirements in § 503.33 (b)(1) through (b)(8) is met.

(b) *Domestic septage*. When domestic septage is applied to agricultural land, forest, or a reclamation site, the person who applies the domestic septage shall develop the following information and shall retain the information for five years:

(1) The location, by either street address or latitude and longitude, of each site on which domestic septage is applied.

(2) The number of acres in each site on which domestic septage is applied.

(3) The date and time domestic septage is applied to each site.

(4) The nitrogen requirement for the crop or vegetation grown on each site during a 365 day period.

(5) The rate, in gallons per acre per 365 day period, at which domestic septage is applied to each site.

(6) The following certification statement:

"I certify, under penalty of law, that the pathogen requirements in [insert either § 503.32(c)(1) or § 503.32(c)(2)] and the vector attraction reduction requirements in [insert § 503.33(b)(9), § 503.33(b)(10), or § 503.33(b)(12)] have been met. This determination has been made under my

direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine that the pathogen requirements and vector attraction reduction requirements have been met. I am aware that there are significant penalties for false certification including the possibility of fine and imprisonment."

(7) A description of how the pathogen requirements in either § 503.33 (c)(1) or (c)(2) are met.

(8) A description of how the vector attraction reduction requirements in § 503.33 (b)(9), (b)(10), or (b)(12) are met.

(Approved by the Office of Management and Budget under control number 2040-0157)

§ 503.18 Reporting.

(a) *Class I sludge management facilities*, POTWs (as defined in 40 CFR 501.2) with a design flow rate equal to or greater than one million gallons per day, and POTWs that serve 10,000 people or more shall submit the following information to the permitting authority:

(1) The information in § 503.17(a), except the information in § 503.17 (a)(3)(ii), (a)(4)(ii) and in (a)(5)(ii), for the appropriate requirements on February 19 of each year.

(2) The information in § 503.17 (a)(5)(ii)(A) through (a)(5)(ii)(G) on [insert the month and day from the date of publication of this rule] of each year when 90 percent or more of any of the cumulative pollutant loading rates in Table 2 of § 503.13 is reached at a site.

(Approved by the Office of Management and Budget under control number 2040-0157)

Subpart C—Surface Disposal

§ 503.20 Applicability.

(a) This subpart applies to any person who prepares sewage sludge that is placed on a surface disposal site, to the owner/operator of a surface disposal site, to sewage sludge placed on a surface disposal site, and to a surface disposal site.

(b) This subpart does not apply to sewage sludge stored on the land or to the land on which sewage sludge is stored. It also does not apply to sewage sludge that remains on the land for longer than two years when the person who prepares the sewage sludge demonstrates that the land on which the sewage sludge remains is not an active sewage sludge unit. The demonstration shall include the following information, which shall be retained by the person who prepares the sewage sludge for the period that the sewage sludge remains on the land:

(1) The name and address of the person who prepares the sewage sludge.

(2) The name and address of the person who either owns the land or leases the land.

(3) The location, by either street address or latitude and longitude, of the land.

(4) An explanation of why sewage sludge needs to remain on the land for longer than two years prior to final use or disposal.

(5) The approximate time period when the sewage sludge will be used or disposed.

(c) This subpart does not apply to sewage sludge treated on the land or to the land on which sewage sludge is treated.

§ 503.21 Special definitions.

(a) *Active sewage sludge unit* is a sewage sludge unit that has not closed.

(b) *Aquifer* is a geologic formation, group of geologic formations, or a portion of a geologic formation capable of yielding ground water to wells or springs.

(c) *Contaminate an aquifer* means to introduce a substance that causes the maximum contaminant level for nitrate in 40 CFR 141.11 to be exceeded in ground water or that causes the existing concentration of nitrate in ground water to increase when the existing concentration of nitrate in the ground water exceeds the maximum contaminant level for nitrate in 40 CFR 141.11.

(d) *Cover* is soil or other material used to cover sewage sludge placed on an active sewage sludge unit.

(e) *Displacement* is the relative movement of any two sides of a fault measured in any direction.

(f) *Fault* is a fracture or zone of fractures in any materials along which strata on one side are displaced with respect to strata on the other side.

(g) *Final cover* is the last layer of soil or other material placed on a sewage sludge unit at closure.

(h) *Holocene time* is the most recent epoch of the Quaternary period, extending from the end of the Pleistocene epoch to the present.

(i) *Leachate collection system* is a system or device installed immediately above a liner that is designed, constructed, maintained, and operated to collect and remove leachate from a sewage sludge unit.

(j) *Liner* is soil or synthetic material that has a hydraulic conductivity of 1×10^{-7} centimeters per second or less.

(k) *Lower explosive limit for methane gas* is the lowest percentage of methane gas in air, by volume, that propagates a flame at 25 degrees Celsius and atmospheric pressure.

(l) *Qualified ground-water scientist* is an individual with a baccalaureate or

post-graduate degree in the natural sciences or engineering who has sufficient training and experience in ground-water hydrology and related fields, as may be demonstrated by State registration, professional certification, or completion of accredited university programs, to make sound professional judgments regarding ground-water monitoring, pollutant fate and transport, and corrective action.

(m) *Seismic impact zone* is an area that has a 10 percent or greater probability that the horizontal ground level acceleration of the rock in the area exceeds 0.10 gravity once in 250 years.

(n) *Sewage sludge unit* is land on which only sewage sludge is placed for final disposal. This does not include land on which sewage sludge is either stored or treated. Land does not include waters of the United States, as defined in 40 CFR 122.2.

(o) *Sewage sludge unit boundary* is the outermost perimeter of an active sewage sludge unit.

(p) *Surface disposal site* is an area of land that contains one or more active sewage sludge units.

(q) *Unstable area* is land subject to natural or human-induced forces that may damage the structural components of an active sewage sludge unit. This includes, but is not limited to, land on which the soils are subject to mass movement.

§ 503.22 General requirements.

(a) No person shall place sewage sludge on an active sewage sludge unit unless the requirements in this subpart are met.

(b) An active sewage sludge unit located within 60 meters of a fault that has displacement in Holocene time; located in an unstable area; or located in a wetland, except as provided in a permit issued pursuant to section 402 of the CWA, shall close by [insert date one year after the effective date of this Final rule], unless, in the case of an active sewage sludge unit located within 60 meters of a fault that has displacement in Holocene time, otherwise specified by the permitting authority.

(c) The owner/operator of an active sewage sludge unit shall submit a written closure and post closure plan to the permitting authority 180 days prior to the date that the active sewage sludge unit closes. The plan shall describe how the sewage sludge unit will be closed and, at a minimum, shall include:

(1) A discussion of how the leachate collection system will be operated and maintained for three years after the sewage sludge unit closes if the sewage sludge unit has a liner and leachate collection system.

(2) A description of the system used to monitor for methane gas in the air in any structures within the surface disposal site and in the air at the property line of the surface disposal site, as required in § 503.24(j)(2).

(3) A discussion of how public access to the surface disposal site will be restricted for three years after the last sewage sludge unit in the surface disposal site closes.

(d) The owner of a surface disposal site shall provide written notification to the subsequent owner of the site that sewage sludge was placed on the land.

§ 503.23 Pollutant limits (other than domestic septage).

(a) Active sewage sludge unit without a liner and leachate collection system.

(1) Except as provided in § 503.23 (a)(2) and (b), the concentration of each pollutant listed in Table 1 of § 503.23 in sewage sludge placed on an active sewage sludge unit shall not exceed the concentration for the pollutant in Table 1 of § 503.23.

TABLE 1 OF § 503.23.—POLLUTANT CONCENTRATIONS—ACTIVE SEWAGE SLUDGE UNIT WITHOUT A LINER AND LEACHATE COLLECTION

Pollutant	Concentration (milligrams per kilogram ¹)
Arsenic _____	73
Chromium _____	600
Nickel _____	420

¹ Dry weight basis.

(2) Except as provided in § 503.23(b), the concentration of each pollutant listed in Table 1 of § 503.23 in sewage sludge placed on an active sewage sludge unit whose boundary is less than 150 meters from the property line of the surface disposal site shall not exceed the concentration determined using the following procedure.

(i) The actual distance from the active sewage sludge unit boundary to the property line of the surface disposal site shall be determined.

(ii) The concentration of each pollutant listed in Table 2 of § 503.23 in the sewage sludge shall not exceed the concentration in Table 2 of § 503.23 that corresponds to the actual distance in § 503.23(a)(2)(i).

TABLE 2 OF § 503.23.—POLLUTANT CONCENTRATIONS—ACTIVE SEWAGE SLUDGE UNIT WITHOUT A LINER AND LEACHATE COLLECTION SYSTEM THAT HAS A UNIT BOUNDARY TO PROPERTY LINE DISTANCE LESS THAN 150 METERS

Unit boundary to property line Distance (meters)	Pollutant concentration ¹		
	Arsenic (mg/kg)	Chromium (mg/kg)	Nickel (mg/kg)
0 to less than 25	30	200	210
25 to less than 50	34	220	240
50 to less than 75	39	260	270
75 to less than 100	46	300	320
100 to less than 125	53	360	390
125 to less than 150	62	450	420

¹ Dry weight basis.

(b) Active sewage sludge unit without a liner and leachate collection system—site-specific limits.

(1) At the time of permit application, the owner/operator of a surface disposal site may request site-specific pollutant limits in accordance with § 503.23(b)(2) for an active sewage sludge unit without a liner and leachate collection system when the existing values for site parameters specified by the permitting authority are different from the values for those parameters used to develop the pollutant limits in Table 1 of § 503.23 and when the permitting authority determines that site-specific pollutant limits are appropriate for the active sewage sludge unit.

(2) The concentration of each pollutant listed in Table 1 of § 503.23 in sewage sludge placed on an active sewage sludge unit without a liner and leachate collection system shall not exceed either the concentration for the pollutant determined during a site-specific assessment, as specified by the permitting authority, or the existing concentration of the pollutant in the sewage sludge, whichever is lower.

§ 503.24 Management practices.

(a) Sewage sludge shall not be placed on an active sewage sludge unit if it is likely to adversely affect a threatened or endangered species listed under section 4 of the Endangered Species Act or its designated critical habitat.

(b) An active sewage sludge unit shall not restrict the flow of a base flood.

(c) When a surface disposal site is located in a seismic impact zone, an active sewage sludge unit shall be designed to withstand the maximum recorded horizontal ground level acceleration.

(d) An active sewage sludge unit shall be located 60 meters or more from a fault that has displacement in Holocene

time, unless otherwise specified by the permitting authority.

(e) An active sewage sludge unit shall not be located in an unstable area.

(f) An active sewage sludge unit shall not be located in a wetland, except as provided in a permit issued pursuant to section 402 or 404 of the CWA.

(g)(1) Run-off from an active sewage sludge unit shall be collected and shall be disposed in accordance with National Pollutant Discharge Elimination System permit requirements and any other applicable requirements.

(2) The run-off collection system for an active sewage sludge unit shall have the capacity to handle run-off from a 24-hour, 25-year storm event.

(h) The leachate collection system for an active sewage sludge unit that has a liner and leachate collection system shall be operated and maintained during the period the sewage sludge unit is active and for three years after the sewage sludge unit closes.

(i) Leachate from an active sewage sludge unit that has a liner and leachate collection system shall be collected and shall be disposed in accordance with the applicable requirements during the period the sewage sludge unit is active and for three years after the sewage sludge unit closes.

(j)(1) When a cover is placed on an active sewage sludge unit, the concentration of methane gas in air in any structure within the surface disposal site shall not exceed 25 percent of the lower explosive limit for methane gas during the period that the sewage sludge unit is active and the concentration of methane gas in air at the property line of the surface disposal site shall not exceed the lower explosive limit for methane gas during the period that the sewage sludge unit is active.

(2) When a final cover is placed on a sewage sludge unit at closure, the concentration of methane gas in air in any structure within the surface disposal site shall not exceed 25 percent of the lower explosive limit for methane gas for three years after the sewage sludge unit closes and the concentration of methane gas in air at the property line of the surface disposal site shall not exceed the lower explosive limit for methane gas for three years after the sewage sludge unit closes, unless otherwise specified by the permitting authority.

(k) A food crop, a feed crop, or a fiber crop shall not be grown on an active sewage sludge unit, unless the owner/operator of the surface disposal site demonstrates to the permitting authority that through management practices public health and the environment are

protected from any reasonably anticipated adverse effects of pollutants in sewage sludge when crops are grown.

(l) Animals shall not be grazed on an active sewage sludge unit, unless the owner/operator of the surface disposal site demonstrates to the permitting authority that through management practices public health and the environment are protected from any reasonably anticipated adverse effects of pollutants in sewage sludge when animals are grazed.

(m) Public access to a surface disposal site shall be restricted for the period that the surface disposal site contains an active sewage sludge unit and for three years after the last active sewage sludge unit in the surface disposal site closes.

(n)(1) Sewage sludge placed on an active sewage sludge unit shall not contaminate an aquifer.

(2) Results of a ground-water monitoring program developed by a qualified ground-water scientist or a certification by a qualified ground-water scientist shall be used to demonstrate that sewage sludge placed on an active sewage sludge unit does not contaminate an aquifer.

§ 503.25 Operational standards—pathogens and vector attraction reduction.

(a) *Pathogens—sewage sludge (other than domestic septage).* The Class A pathogens requirements in § 503.32(a) or one of the Class B pathogen requirements in § 503.32 (b)(2) through (b)(4) shall be met when sewage sludge is placed on an active sewage sludge unit, unless the vector attraction reduction requirement in § 503.33(b)(11) is met.

(b) *Vector attraction reduction—sewage sludge (other than domestic septage).* One of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(11) shall be met when sewage sludge is placed on an active sewage sludge unit.

(c) *Vector attraction reduction—domestic septage.* One of the vector attraction reduction requirement in § 503.33 (b)(9) through (b)(12) shall be met when domestic septage is placed on an active sewage sludge unit.

§ 503.26 Frequency of monitoring.

(a) *Sewage sludge (other than domestic septage).*

(1) The frequency of monitoring for the pollutants in Tables 1 and 2 of § 503.23; the pathogen density requirements in § 503.32(a) and in § 503.32 (b)(2) through (b)(4); and the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8) for sewage sludge placed on an active sewage sludge unit shall be the frequency in Table 1 of § 503.26.

TABLE 1 OF § 503.26.—FREQUENCY OF MONITORING—SURFACE DISPOSAL

Amount of sewage sludge ¹ (metric tons per 365 day period)	Frequency
Greater than zero but less than 250.	Once per year.
Equal to or greater than 250 but less than 1,500.	Once per quarter (four times per year).
Equal to or greater than 1,500 but less than 15,000.	Once per 60 days (six times per year).
Equal to or greater than 15,000.	Once per month (12 times per year).

¹ Amount of sewage sludge placed on an active sewage sludge unit (dry weight basis).

(2) After the sewage sludge has been monitored for two years at the frequency in Table 1 of § 503.26, the permitting authority may reduce the frequency of monitoring for pollutant concentrations and for the pathogen density requirements in § 503.32 (a)(5)(iii) and (a)(5)(iii), but in no case shall the frequency of monitoring be less than once per year when sewage sludge is placed on an active sewage sludge unit.

(b) *Domestic septage.* If the vector attraction reduction requirements in § 503.33(b)(12) are met when domestic septage is placed on an active sewage sludge unit, each container of domestic septage shall be monitored for compliance with those requirements.

(c) *Air.* Air in structures within a surface disposal site and at the property line of the surface disposal site shall be monitored continuously for methane gas during the period that the surface disposal site contains an active sewage sludge unit on which the sewage sludge is covered and for three years after a sewage sludge unit closes when a final cover is placed on the sewage sludge.

(Approved by the Office of Management and Budget under control number 2640-0157)

§ 503.27 Recordkeeping.

(a) When sewage sludge (other than domestic septage) is placed on an active sewage sludge unit:

(1) The person who prepares the sewage sludge shall develop the following information and shall retain the information for five years.

(i) The concentration of each pollutant listed in Table 1 of § 503.23 in the sewage sludge when the pollutant concentrations in Table 1 of § 503.23 are met.

(ii) The following certification statement:

"I certify, under penalty of law, that the pathogen requirements in insert § 503.32(a), § 503.32(b)(2), § 503.32(b)(3), or § 503.32(b)(4) when one of those requirements is met) and the vector attraction reduction requirements in insert one of the vector attraction

reduction requirements in § 503.33(b)(1) through § 503.33(b)(8) when one of those requirements is met] have been met. This determination has been made under my direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine the [pathogen requirements and vector attraction reduction requirements if appropriate] have been met. I am aware that there are significant penalties for false certification including the possibility of fine and imprisonment."

(iii) A description of how the pathogen requirements in § 503.32 (a), (b)(2), (b)(3), or (b)(4) are met when one of those requirements is met.

(iv) A description of how one of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8) is met when one of those requirements is met.

(2) The owner/operator of the surface disposal site, shall develop the following information and shall retain that information for five years:

(i) The concentration of each pollutant listed in Table 2 of § 503.23 in the sewage sludge when the pollutant concentrations in Table 2 of § 503.23 are met or when site-specific pollutant limits in § 503.23(b) are met.

(ii) The following certification statement:

"I certify, under penalty of law, that the management practices in § 503.24 and the vector attraction reduction requirement in [insert one of the requirements in § 503.33 (b)(9) through (b)(11) if one of those requirements is met] have been met. This determination has been made under my direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine that the management practices [and the vector attraction reduction requirements if appropriate] have been met. I am aware that there are significant penalties for false certification including the possibility of fine and imprisonment."

(iii) A description of how the management practices in § 503.24 are met.

(iv) A description of how the vector attraction reduction requirements in § 503.33 (b)(9) through (b)(11) are met if one of those requirements is met.

(b) When domestic septage is placed on a surface disposal site:

(1) If the vector attraction reduction requirements in § 503.33(b)(12) are met, the person who places the domestic septage on the surface disposal site shall develop the following information and shall retain the information for five years:

(i) The following certification statement:

"I certify, under penalty of law, that the vector attraction reduction requirements in

§ 503.33(b)(12) have been met. This determination has been made under my direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine that the vector attraction requirements have been met. I am aware that there are significant penalties for false certification including the possibility of fine and imprisonment."

(ii) A description of how the vector attraction reduction requirements in § 503.33(b)(12) are met.

(2) The owner/operator of the surface disposal site shall develop the following information and shall retain that information for five years:

(i) The following certification statement:

"I certify, under penalty of law, that the management practices in § 503.24 and the vector attraction reduction requirements in [insert § 503.33(b)(9) through § 503.33(b)(11) when one of those requirements is met] have been met. This determination has been made under my direction and supervision in accordance with the system designed to ensure that qualified personnel properly gather and evaluate the information used to determine that the management practices [and the vector attraction reduction requirements if appropriate] have been met. I am aware that there are significant penalties for false certification including the possibility of fine or imprisonment."

(ii) A description of how the management practices in § 503.24 are met.

(iii) A description how the vector attraction reduction requirements in § 503.33(b)(9) through § 503.33(b)(11) are met if one of those requirements is met.

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§ 503.28 Reporting.

Class I sludge management facilities, POTWs (as defined in 40 CFR 501.2) with a design flow rate equal to or greater than one million gallons per day, and POTWs that serve 10,000 people or more shall submit the information in § 503.27(a) to the permitting authority on February 19 of each year.

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Subpart D—Pathogens and Vector Attraction Reduction

§ 503.30 Scope.

(a) This subpart contains the requirements for a sewage sludge to be classified either Class A or Class B with respect to pathogens.

(b) This subpart contains the site restrictions for land on which a Class B sewage sludge is applied.

(c) This subpart contains the pathogen requirements for domestic septage

applied to agricultural land, forest, or a reclamation site.

(d) This subpart contains alternative vector attraction reduction requirements for sewage sludge that is applied to the land or placed on a surface disposal site.

§ 503.31 Special definitions.

(a) *Aerobic digestion* is the biochemical decomposition of organic matter in sewage sludge into carbon dioxide and water by microorganisms in the presence of air.

(b) *Anaerobic digestion* is the biochemical decomposition of organic matter in sewage sludge into methane gas and carbon dioxide by microorganisms in the absence of air.

(c) *Density of microorganisms* is the number of microorganisms per unit mass of total solids (dry weight) in the sewage sludge.

(d) *Land with a high potential for public exposure* is land that the public uses frequently. This includes, but is not limited to, a public contact site and a reclamation site located in a populated area (e.g., a construction site located in a city).

(e) *Land with a low potential for public exposure* is land that the public uses infrequently. This includes, but is not limited to, agricultural land, forest, and a reclamation site located in an unpopulated area (e.g., a strip mine located in a rural area).

(f) *Pathogenic organisms* are disease-causing organisms. These include, but are not limited to, certain bacteria, protozoa, viruses, and viable helminth ova.

(g) *pH* means the logarithm of the reciprocal of the hydrogen ion concentration.

(h) *Specific oxygen uptake rate (SOUR)* is the mass of oxygen consumed per unit time per unit mass of total solids (dry weight basis) in the sewage sludge.

(i) *Total solids* are the materials in sewage sludge that remain as residue when the sewage sludge is dried at 103 to 105 degrees Celsius.

(j) *Unstabilized solids* are organic materials in sewage sludge that have not been treated in either an aerobic or anaerobic treatment process.

(k) *Vector attraction* is the characteristic of sewage sludge that attracts rodents, flies, mosquitos, or other organisms capable of transporting infectious agents.

(l) *Volatile solids* is the amount of the total solids in sewage sludge lost when the sewage sludge is combusted at 550 degrees Celsius in the presence of excess air.

§ 503.32 Pathogens.

(a) *Sewage sludge—Class A.* (1) The requirement in § 503.32(a)(2) and the requirements in either § 503.32(a)(3), (a)(4), (a)(5), (a)(6), (a)(7), or (a)(8) shall be met for a sewage sludge to be classified Class A with respect to pathogens.

(2) The Class A pathogen requirements in § 503.32 (a)(3) through (a)(8) shall be met either prior to meeting or at the same time the vector attraction reduction requirements in § 503.33, except the vector attraction reduction requirements in § 503.33 (b)(6) through (b)(8), are met.

(3) *Class A—Alternative 1.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) The temperature of the sewage sludge that is used or disposed shall be maintained at a specific value for a period of time.

(A) When the percent solids of the sewage sludge is seven percent or higher, the temperature of the sewage sludge shall be 50 degrees Celsius or higher; the time period shall be 20 minutes or longer; and the temperature and time period shall be determined using equation (2), except when small particles of sewage sludge are heated by either warmed gases or an immiscible liquid.

$$D = \frac{131,700,000}{10^{0.1400t}} \quad \text{Eq. (2)}$$

Where,

D=time in days.

t=temperature in degrees Celsius.

(B) When the percent solids of the sewage sludge is seven percent or higher and small particles of sewage sludge are heated by either warmed gases or an immiscible liquid, the temperature of the sewage sludge shall be 50 degrees Celsius or higher; the time period shall be 15 seconds or longer; and the temperature and time period shall be determined using equation (2).

(C) When the percent solids of the sewage sludge is less than seven percent and the time period is at least 15

seconds, but less than 30 minutes, the temperature and time period shall be determined using equation (2).

(D) When the percent solids of the sewage sludge is less than seven percent; the temperature of the sewage sludge is 50 degrees Celsius or higher; and the time period is 30 minutes or longer, the temperature and time period shall be determined using equation (3).

$$D = \frac{50,070,000}{10^{0.1400t}} \quad \text{Eq. (3)}$$

Where,

D=time in days.

t=temperature in degrees Celsius.

(4) *Class A—Alternative 2.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) (A) The pH of the sewage sludge that is used or disposed shall be raised to above 12 and shall remain above 12 for 72 hours.

(B) The temperature of the sewage sludge shall be above 52 degrees Celsius for 12 hours or longer during the period that the pH of the sewage sludge is above 12.

(C) At the end of the 72 hour period during which the pH of the sewage sludge is above 12, the sewage sludge shall be air dried to achieve a percent solids in the sewage sludge greater than 50 percent.

(5) *Class A—Alternative 3.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) (A) The sewage sludge shall be analyzed prior to pathogen treatment to

determine whether the sewage sludge contains enteric viruses.

(B) When the density of enteric viruses in the sewage sludge prior to pathogen treatment is less than one Plaque-forming Unit per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to enteric viruses until the next monitoring episode for the sewage sludge.

(C) When the density of enteric viruses in the sewage sludge prior to pathogen treatment is equal to or greater than one Plaque-forming Unit per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to enteric viruses when the density of enteric viruses in the sewage sludge after pathogen treatment is less than one Plaque-forming Unit per four grams of total solids (dry weight basis) and when the values or ranges of values for the operating parameters for the pathogen treatment process that produces the sewage sludge that meets the enteric virus density requirement are documented.

(D) After the enteric virus reduction in paragraph (a)(5)(ii)(C) of this section is demonstrated for the pathogen treatment process, the sewage sludge continues to be Class A with respect to enteric viruses when the values for the pathogen treatment process operating parameters are consistent with the values or ranges of values documented in paragraph (a)(5)(ii)(C) of this section.

(iii)(A) The sewage sludge shall be analyzed prior to pathogen treatment to determine whether the sewage sludge contains viable helminth ova.

(B) When the density of viable helminth ova in the sewage sludge prior to pathogen treatment is less than one per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to viable helminth ova until the next monitoring episode for the sewage sludge.

(C) When the density of viable helminth ova in the sewage sludge prior to pathogen treatment is equal to or greater than one per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to viable helminth ova when the density of viable helminth ova in the sewage sludge after pathogen treatment is less than one per four grams of total solids (dry weight basis) and when the values or ranges of values for the operating parameters for the pathogen treatment process that produces the sewage sludge that meets the viable helminth ova density requirement are documented.

(D) After the viable helminth ova reduction in paragraph (a)(5)(iii)(C) of this section is demonstrated for the pathogen treatment process, the sewage

sludge continues to be Class A with respect to viable helminth ova when the values for the pathogen treatment process operating parameters are consistent with the values or ranges of values documented in paragraph (a)(5)(iii)(C) of this section.

(6) *Class A—Alternative 4.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) The density of enteric viruses in the sewage sludge shall be less than one Plaque-forming Unit per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f), unless otherwise specified by the permitting authority.

(iii) The density of viable helminth ova in the sewage sludge shall be less than one per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f), unless otherwise specified by the permitting authority.

(7) *Class A—Alternative 5.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella*, sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or given away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10(b), (c), (e), or (f).

(ii) Sewage sludge that is used or disposed shall be treated in one of the Processes to Further Reduce Pathogens described in appendix B of this part.

(8) *Class A—Alternative 6.* (i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella*, sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or given away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10(b), (c), (e), or (f).

(ii) Sewage sludge that is used or disposed shall be treated in a process that is equivalent to a Process to Further Reduce Pathogens, as determined by the permitting authority.

(b) *Sewage sludge—Class B.* (1)(i) The requirements in either § 503.32(b)(2), (b)(3), or (b)(4) shall be met for a sewage sludge to be classified Class B with respect to pathogens.

(ii) The site restrictions in § 503.32(b)(5) shall be met when sewage sludge that meets the Class B pathogen requirements in § 503.32(b)(2), (b)(3), or (b)(4) is applied to the land.

(2) *Class B—Alternative 1.*

(i) Seven samples of the sewage sludge shall be collected at the time the sewage sludge is used or disposed.

(ii) The geometric mean of the density of fecal coliform in the samples collected in paragraph (b)(2)(i) of this section shall be less than either 2,000,000 Most Probable Number per gram of total solids (dry weight basis) or 2,000,000 Colony Forming Units per gram of total solids (dry weight basis).

(3) *Class B—Alternative 2.* Sewage sludge that is used or disposed shall be treated in one of the Processes to Significantly Reduce Pathogens described in appendix B of this part.

(4) *Class B—Alternative 3.* Sewage sludge that is used or disposed shall be treated in a process that is equivalent to a Process to Significantly Reduce Pathogens, as determined by the permitting authority.

(5) *Site Restrictions.* (i) Food crops with harvested parts that touch the sewage sludge/soil mixture and are totally above the land surface shall not be harvested for 14 months after application of sewage sludge.

(ii) Food crops with harvested parts below the surface of the land shall not be harvested for 20 months after application of sewage sludge when the

sewage sludge remains on the land surface for four months or longer prior to incorporation into the soil.

(iii) Food crops with harvested parts below the surface of the land shall not be harvested for 38 months after application of sewage sludge when the sewage sludge remains on the land surface for less than four months prior to incorporation into the soil.

(iv) Food crops, feed crops, and fiber crops shall not be harvested for 30 days after application of sewage sludge.

(v) Animals shall not be allowed to graze on the land for 30 days after application of sewage sludge.

(vi) Turf grown on land where sewage sludge is applied shall not be harvested for one year after application of the sewage sludge when the harvested turf is placed on either land with a high potential for public exposure or a lawn; unless otherwise specified by the permitting authority.

(vii) Public access to land with a high potential for public exposure shall be restricted for one year after application of sewage sludge.

(viii) Public access to land with a low potential for public exposure shall be restricted for 30 days after application of sewage sludge.

(c) *Domestic septage.* (1) The site restrictions in § 503.32(b)(5) shall be met when domestic septage is applied to agricultural land, forest, or a reclamation site; or

(2) The pH of domestic septage applied to agricultural land, forest, or a reclamation site shall be raised to 12 or higher by alkali addition and, without the addition of more alkali, shall remain at 12 or higher for 30 minutes and the site restrictions in § 503.32 (b)(5)(i) through (b)(5)(iv) shall be met.

§ 503.33 Vector attraction reduction.

(a)(1) One of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(10) shall be met when bulk sewage sludge is applied to agricultural land, forest, a public contact site, or a reclamation site.

(2) One of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8) shall be met when bulk sewage sludge is applied to a lawn or a home garden.

(3) One of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(8) shall be met when sewage sludge is sold or given away in a bag or other container for application to the land.

(4) One of the vector attraction reduction requirements in § 503.33 (b)(1) through (b)(11) shall be met when sewage sludge (other than domestic

septage) is placed on an active sewage sludge unit.

(5) One of the vector attraction reduction requirements in § 503.33 (b)(9), (b)(10), or (b)(12) shall be met when domestic septage is applied to agricultural land, forest, or a reclamation site and one of the vector attraction reduction requirements in § 503.33 (b)(9) through (b)(12) shall be met when domestic septage is placed on an active sewage sludge unit.

(b)(1) The mass of volatile solids in the sewage sludge shall be reduced by a minimum of 38 percent (see calculation procedures in "Environmental Regulations and Technology—Control of Pathogens and Vector Attraction in Sewage Sludge", EPA-625/R-92/013, 1992, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268).

(2) When the 38 percent volatile solids reduction requirement in § 503.33(b)(1) cannot be met for an anaerobically digested sewage sludge, vector attraction reduction can be demonstrated by digesting a portion of the previously digested sewage sludge anaerobically in the laboratory in a bench-scale unit for 40 additional days at a temperature between 30 and 37 degrees Celsius. When at the end of the 40 days, the volatile solids in the sewage sludge at the beginning of that period is reduced by less than 17 percent, vector attraction reduction is achieved.

(3) When the 38 percent volatile solids reduction requirement in § 503.33(b)(1) cannot be met for an aerobically digested sewage sludge, vector attraction reduction can be demonstrated by digesting a portion of the previously digested sewage sludge that has a percent solids of two percent or less aerobically in the laboratory in a bench-scale unit for 30 additional days at 20 degrees Celsius. When at the end of the 30 days, the volatile solids in the sewage sludge at the beginning of that period is reduced by less than 15 percent, vector attraction reduction is achieved.

(4) The specific oxygen uptake rate (SOUR) for sewage sludge treated in an aerobic process shall be equal to or less than 1.5 milligrams of oxygen per hour per gram of total solids (dry weight basis) at a temperature of 20 degrees Celsius.

(5) Sewage sludge shall be treated in an aerobic process for 14 days or longer. During that time, the temperature of the sewage sludge shall be higher than 40 degrees Celsius and the average temperature of the sewage sludge shall be higher than 45 degrees Celsius.

(6) The pH of sewage sludge shall be raised to 12 or higher by alkali addition and, without the addition of more alkali, shall remain at 12 or higher for two hours and then at 11.5 or higher for an additional 22 hours.

(7) The percent solids of sewage sludge that does not contain unstabilized solids generated in a primary wastewater treatment process shall be equal to or greater than 75 percent based on the moisture content and total solids prior to mixing with other materials.

(8) The percent solids of sewage sludge that contains unstabilized solids generated in a primary wastewater treatment process shall be equal to or greater than 90 percent based on the moisture content and total solids prior to mixing with other materials.

(9)(i) Sewage sludge shall be injected below the surface of the land.

(ii) No significant amount of the sewage sludge shall be present on the land surface within one hour after the sewage sludge is injected.

(iii) When the sewage sludge that is injected below the surface of the land is Class A with respect to pathogens, the sewage sludge shall be injected below the land surface within eight hours after being discharged from the pathogen treatment process.

(10)(i) Sewage sludge applied to the land surface or placed on a surface disposal site shall be incorporated into the soil within six hours after application to or placement on the land.

(ii) When sewage sludge that is incorporated into the soil is Class A with respect to pathogens, the sewage sludge shall be applied to or placed on the land within eight hours after being discharged from the pathogen treatment process.

(11) Sewage sludge placed on an active sewage sludge unit shall be covered with soil or other material at the end of each operating day.

(12) The pH of domestic septage shall be raised to 12 or higher by alkali addition and, without the addition of more alkali, shall remain at 12 or higher for 30 minutes.

Subpart E—Incineration

§ 503.40 Applicability.

(a) This subpart applies to a person who fires sewage sludge in a sewage sludge incinerator, to a sewage sludge incinerator, and to sewage sludge fired in a sewage sludge incinerator.

(b) This subpart applies to the exit gas from a sewage sludge incinerator stack.

§ 503.41 Special definitions.

(a) *Air pollution control device* is one or more processes used to treat the exit

gas from a sewage sludge incinerator stack.

(b) *Auxiliary fuel* is fuel used to augment the fuel value of sewage sludge. This includes, but is not limited to, natural gas, fuel oil, coal, gas generated during anaerobic digestion of sewage sludge, and municipal solid waste (not to exceed 30 percent of the dry weight of sewage sludge and auxiliary fuel together). Hazardous wastes are not auxiliary fuel.

(c) *Control efficiency* is the mass of a pollutant in the sewage sludge fed to an incinerator minus the mass of that pollutant in the exit gas from the incinerator stack divided by the mass of the pollutant in the sewage sludge fed to the incinerator.

(d) *Dispersion factor* is the ratio of the increase in the ground level ambient air concentration for a pollutant at or beyond the property line of the site where the sewage sludge incinerator is located to the mass emission rate for the pollutant from the incinerator stack.

(e) *Fluidized bed incinerator* is an enclosed device in which organic matter and inorganic matter in sewage sludge are combusted in a bed of particles suspended in the combustion chamber gas.

(f) *Hourly average* is the arithmetic mean of all measurements, taken during an hour. At least two measurements must be taken during the hour.

(g) *Incineration* is the combustion of organic matter and inorganic matter in sewage sludge by high temperatures in an enclosed device.

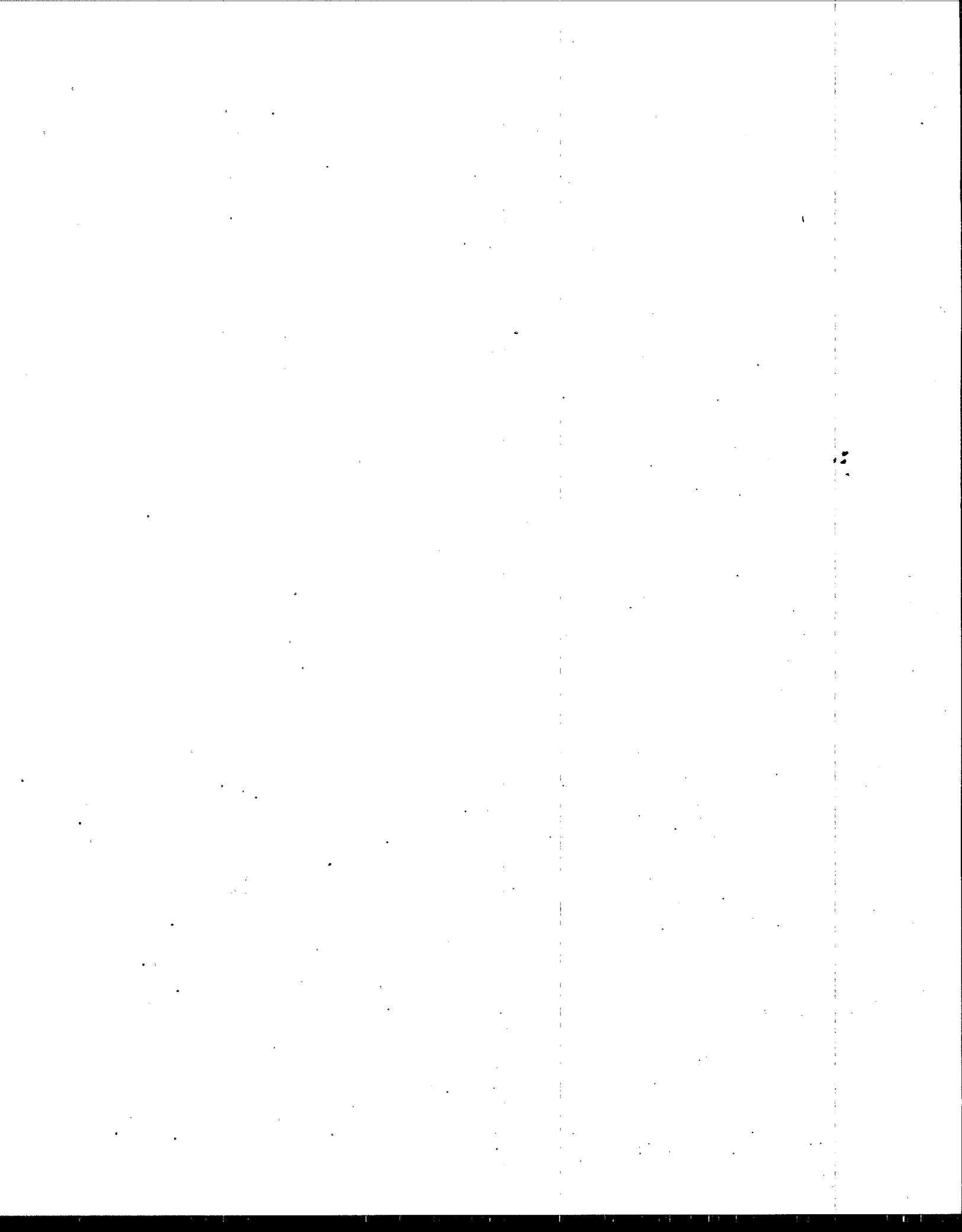
(h) *Monthly average* is the arithmetic mean of the hourly averages for the hours a sewage sludge incinerator operates during the month.

(i) *Risk specific concentration* is the allowable increase in the average daily ground level ambient air concentration for a pollutant from the incineration of sewage sludge at or beyond the property line of the site where the sewage sludge incinerator is located.

(j) *Sewage sludge feed rate* is either the average daily amount of sewage sludge fired in all sewage sludge incinerators within the property line of the site where the sewage sludge incinerators are located for the number of days in a 365 day period that each sewage sludge incinerator operates, or the average daily design capacity for all sewage sludge incinerators within the property line of the site where the sewage sludge incinerators are located.

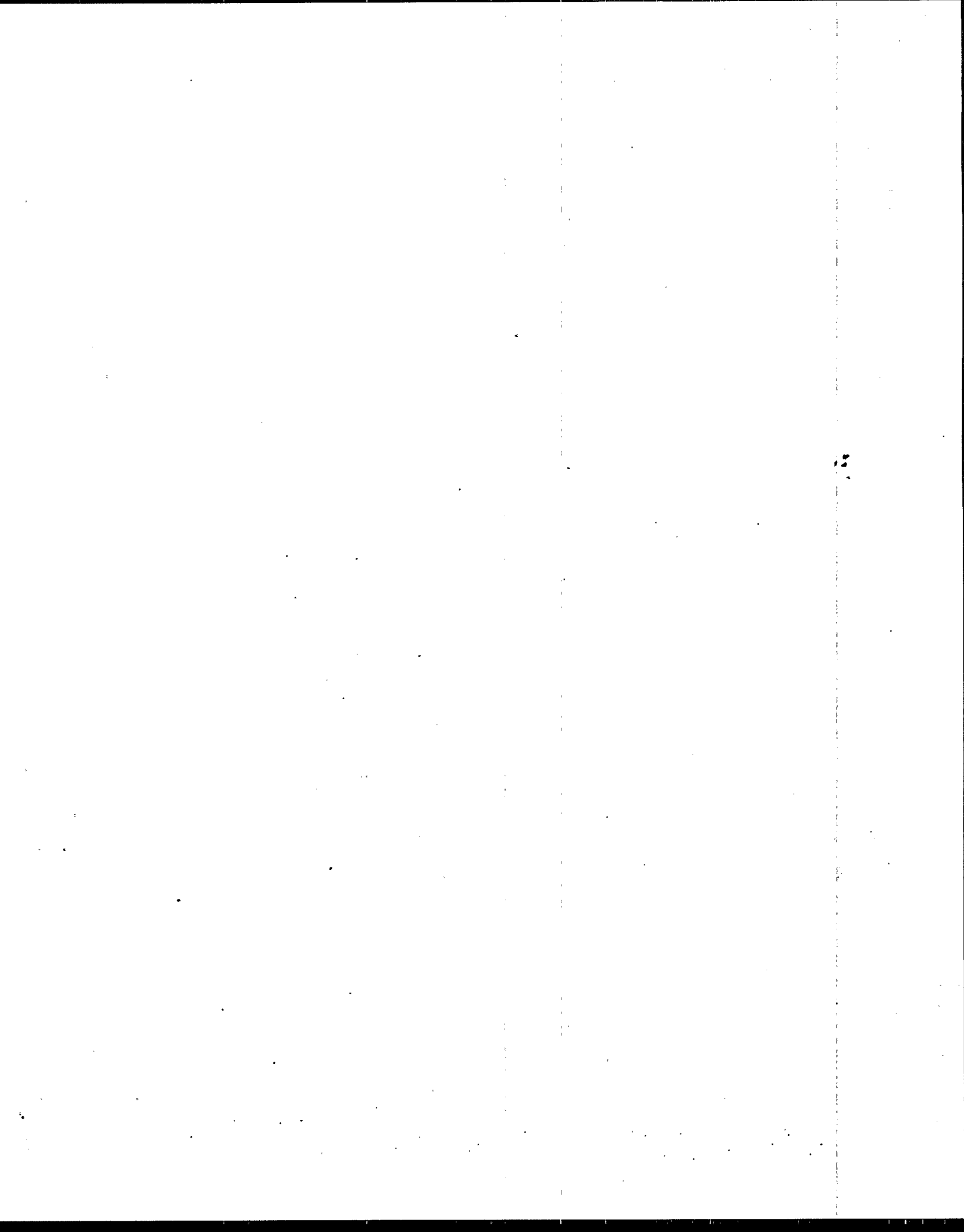
(k) *Sewage sludge incinerator* is an enclosed device in which only sewage sludge and auxiliary fuel are fired.

(l) *Stack height* is the difference between the elevation of the top of a sewage sludge incinerator stack and the



APPENDIX B

PARTITIONING OF CONTAMINANT AMONG AIR, WATER, AND SOLIDS IN SOIL



APPENDIX B

Partitioning of Contaminant Among Air, Water, and Solids in Soil

Calculations used to derive criteria for groundwater, surface water, and air pathways are based on the assumption that equilibrium is maintained between concentrations of contaminant in the air-filled pore space, the water-filled pore space, and the solid particles of soil. Equilibrium partitioning between dissolved and gaseous phases is described by Henry's Law constants; partitioning between adsorbed and dissolved phases is described by soil-water partition coefficients. From these assumptions and the definitions of concentration are derived the equations used to describe partitioning.

Define:

- C_s = concentration of adsorbed contaminant on soil particles (kg/kg),
- C_w = concentration of dissolved contaminant in soil (kg/m³),
- C_a = concentration of gaseous contaminant in soil (kg/m³), and
- C_t = total concentration of contaminant in soil (kg/m³).

Mathematically:

$$C_s = \frac{M_{cs}}{M_s} \quad C_w = \frac{M_{cw}}{V_w} \quad C_a = \frac{M_{ca}}{V_a}$$

and:

$$C_t = \frac{M_{ct}}{V_t} = \frac{M_{cs} + M_{cw} + M_{ca}}{V_a + V_w + V_s}$$

where:

- M_{cs} = mass of adsorbed contaminant (kg),
- M_s = mass of soil (kg),
- M_{cw} = mass of dissolved contaminant (kg),
- V_w = volume of water in soil (m³),

M_{cs}	=	mass of gaseous contaminant (kg),
V_a	=	volume of air in soil (m ³),
M_s	=	total mass of contaminant in soil (kg),
V_t	=	total volume of soil (m ³), and
V_s	=	volume of solids in soil (m ³).

The equilibrium distribution coefficient (KD , in m³/kg) between adsorbed and dissolved phases can be defined as:

$$KD = \frac{[M_{cs}/M_s]}{M_{cw}/V_w} = \frac{M_{cs} V_w}{M_s M_{cw}}$$

The dimensionless Henry's Law constant (\dot{H}) describing the partitioning between gaseous and dissolved phases is defined as:

$$\dot{H} = \frac{[M_{ca}/V_a]}{[M_{cw}/V_w]} = \frac{M_{ca} V_w}{V_a M_{cw}}$$

The bulk density of soil (BD , in kg/m³) is defined as:

$$BD = M_s / V_t$$

The air-filled porosity of soil (θ_a) is defined as:

$$\theta_a = V_a / V_t$$

water-filled porosity (θ_w) as:

$$\theta_w = V_w / V_t$$

and the total porosity of soil (θ_t) is defined as:

$$\theta_t = (V_t - V_s) / V_t = \theta_a + \theta_w$$

The above definitions can be combined to yield:

$$\frac{C_t}{C_a} = \frac{KD BD}{\dot{H}} + \frac{\theta_w}{\dot{H}} + \theta_a$$

and:

$$\frac{C_t}{C_w} = BD KD + \theta_w + \dot{H} \theta_a$$

and:

$$\frac{C_t}{C_s} = BD + \frac{\theta_w}{KD} + \frac{\theta_a \dot{H}}{KD}$$

These relations are used throughout the calculations described in Sections 5.3 and 5.4. Where dry-weight concentrations of contaminant in sludge or soil are involved, the equations are modified slightly, based on the definition:

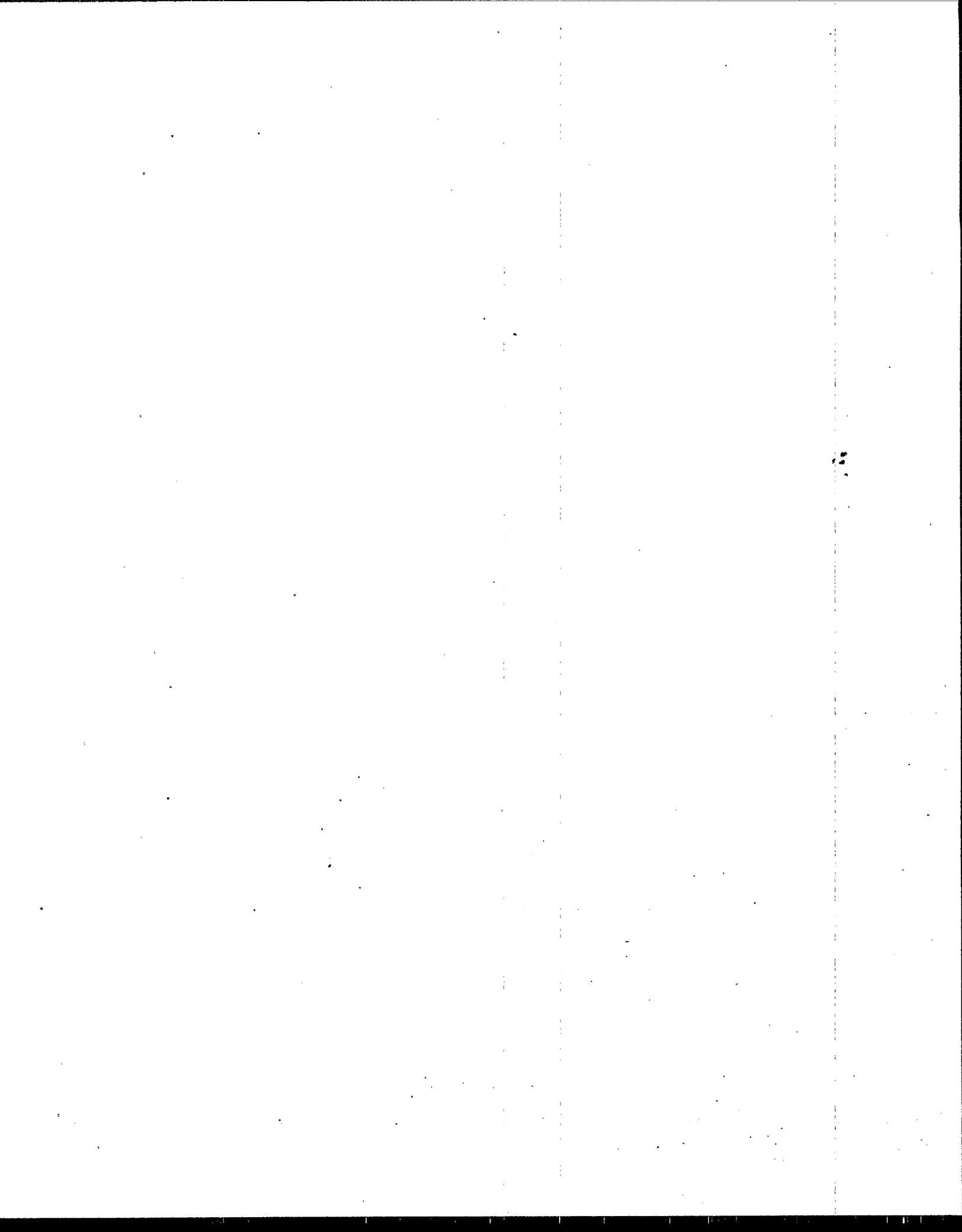
$$C_{dw} = \frac{M_{\alpha}}{M_s} = \frac{M_{\alpha}}{V_t BD} = \frac{C_t}{BD}$$

where:

C_{dw} = dry-weight concentration of contaminant in sludge/soil.

APPENDIX C

DERIVATION OF FIRST-ORDER COEFFICIENT FOR LOSSES TO LEACHING



APPENDIX C

Derivation of First-Order Coefficient for Losses to Leaching

US EPA (1986d) provides an equation for computing a first-order loss rate to leaching for contaminant in treated soil:

$$K_{lec} = \frac{NR}{BD \cdot KD}$$

where:

- K_{lec} = first-order loss rate coefficient for leaching (yr^{-1}),
- NR = annual recharge rate (m/yr),
- BD = bulk density of soil (kg/m^3), and
- KD = soil-water distribution coefficient for contaminant (m^3/kg).

This appendix describes a modified version of that equation.

The basic strategy for deriving a coefficient for first-order loss to leaching is to estimate the mass of contaminant expected to be lost each year and divide by the available mass of contaminant.

The mass of contaminant that will be lost to leaching in any interval of time can be described by the volume of water percolating through the treated soil multiplied by the average concentration of contaminant in that water:

$$FA_l = NR \cdot C_{lec} \cdot 1000$$

where:

- FA_l = flux of leached contaminant from treated soil (kg/ha-yr),
- NR = recharge to groundwater beneath the treated soil ($\text{m}^3/\text{m}^2\text{-yr}$, or m/yr),
- C_{lec} = concentration of contaminant in water infiltrating through the treated soil (kg/m^3), and
- 1000 = constant to convert units from ($\text{kg/m}^2\text{-yr}$) to (kg/ha-yr).

From Appendix B, the concentration of contaminant in leachate is related to the total concentration (by volume) of contaminant in soil as:

$$C_w = C_t / [BD \cdot KD + \theta_w + H \cdot \theta_a]$$

where:

- C_t = total concentration of contaminant in treated soil (kg/m^3),
- θ_w = water-filled porosity of soil (dimensionless),
- H = Henry's Law Constant for contaminant (dimensionless), and
- θ_a = air-filled porosity of soil (dimensionless).

This flux of contaminant must be translated into a first-order loss coefficient so that:

$$\frac{dC_t}{dt} = -K_{lec} C_t$$

where:

- K_{lec} = first-order loss rate coefficient for leaching (yr^{-1}),
- C_t = total concentration of contaminant in soil at time t (g/m^3), and
- t = time (yr).

K_{lec} is estimated with the approximation:

$$K_{lec} = \frac{[dC_t/dt]}{C_t} \approx \frac{[\Delta C_t/\Delta t]}{C_t} = \frac{[\Delta M_{cr}/\Delta t]}{M_{cr}}$$

where:

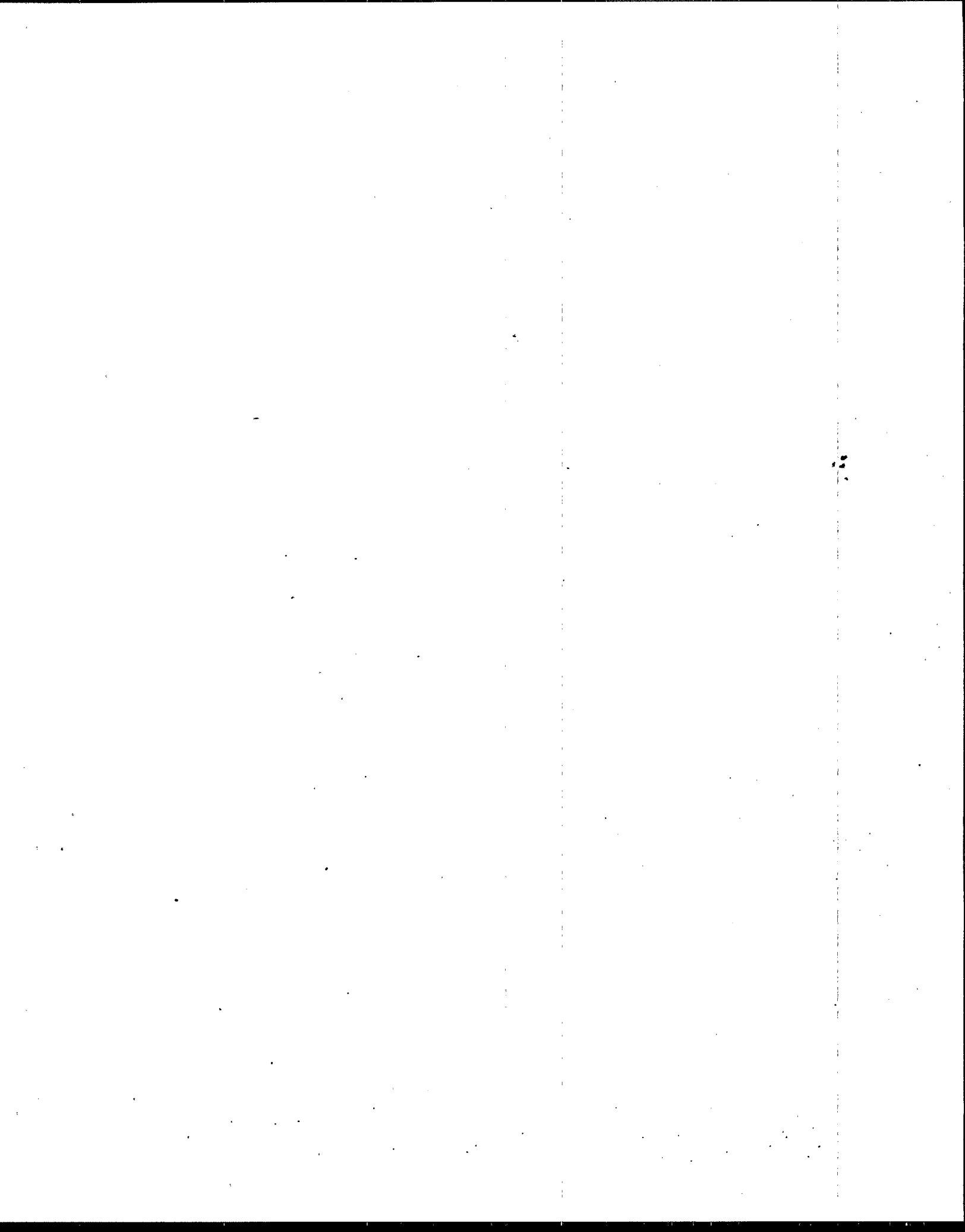
- M_{cr} = mass of contaminant in soil, and
- Δt = one year.

The volume of treated soil beneath one square meter of soil surface (in m^3/m^2) is equal to the depth to which sludge has been incorporated into the soil (d_i in m). The total mass of contaminant beneath one square meter of surface can therefore be described by:

$$M_{ct} = C_t V_t = C_t d_i$$

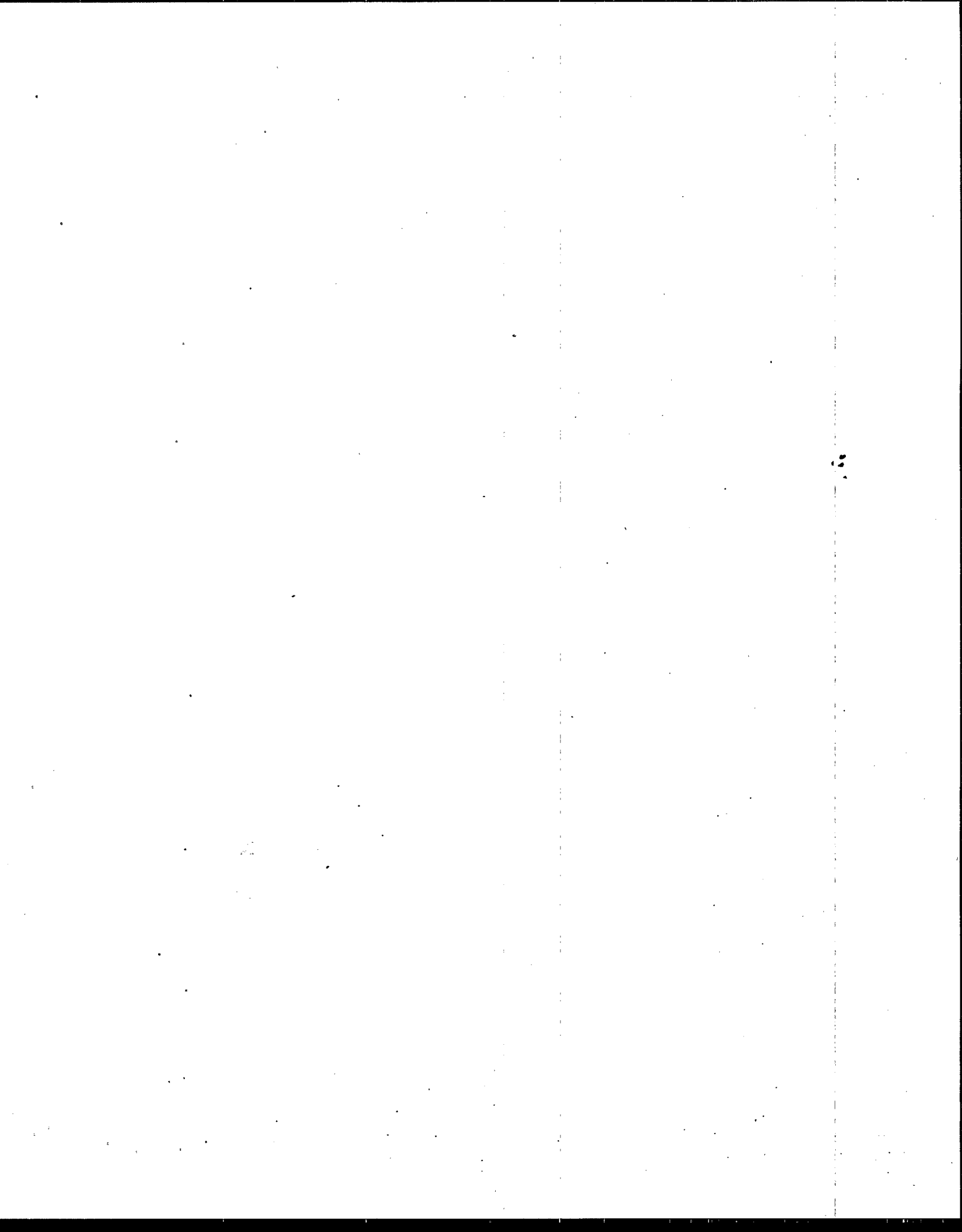
Combining these equations with results from Appendix B yields:

$$K_{lec} \approx \frac{FA_t 10^{-3}}{M_{ct}} = \frac{NR C_{lec}}{C_t V_t} = \frac{NR}{[BD KD + \theta_w + \dot{H} \theta_a] d_i}$$



APPENDIX D

DERIVING A "SQUARE WAVE" FOR THE MONOFILL PROTOTYPE



APPENDIX D

Deriving a "Square Wave" for the Monofill Prototype

Derivation of criteria for surface disposal includes the calculation of a "square wave" as a conservative approximation of the loading of contaminant from the facility to the unsaturated soil zone. This square wave is of magnitude equal to the maximum expected rate of loss of contaminant from the facility (kg/ha-yr) and of a duration calculated to conserve contaminant mass. It is assumed that all competing loss processes for contaminant in soil can be approximated as first-order, and that coefficients describing the rate of loss to each process can be summed to yield a total or "lumped" coefficient for first-order loss. Losses at any time t can be described as:

$$\frac{dM_t}{dt} = -K_{tot} M_t$$

where:

$$\begin{aligned} M_t &= \text{mass of contaminant in treated soil at time } t \text{ (kg/ha), and} \\ K_{tot} &= \text{lumped, first-order loss rate for contaminant (yr}^{-1}\text{).} \end{aligned}$$

If the rate of contaminant loss is proportional to the available mass of contaminant, the maximum rate of loss will occur in the last year of the monofill's operation. The mass of contaminant in the facility after LF years of operation can be approximated by:

$$M_{LF} = \int_0^{LF} AR e^{-K_{tot}x} dx = \frac{AR}{K_{tot}} (1 - e^{-K_{tot} LF})$$

where:

$$AR = \text{annual loading of contaminant to monofill facility (kg/ha-yr).}$$

At that time, the rate of loss will be:

$$K_{tot} M_{LF} = AR(1 - e^{-K_{tot} LF})$$

At that rate, the total loading of contaminant to the facility would be depleted in:

$$TP = \frac{LF \ AR}{K_{ex} \ M_{LF}} = LF / [1 - e^{-K_{ex} \ LF}]$$

APPENDIX E

**JUSTIFICATION FOR THE DELETION OF POLLUTANTS FROM THE
FINAL STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE**

**JUSTIFICATION FOR THE DELETION OF POLLUTANTS FROM THE
FINAL STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE**

**Office of Science and Technology
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460**

November 16, 1992

**JUSTIFICATION FOR THE DELETION OF POLLUTANTS FROM THE
FINAL STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE**

TABLE OF CONTENTS

1.	INTRODUCTION	E-1
2.	ORGANIC POLLUTANTS - LAND APPLICATION AND SURFACE DISPOSAL	
2.1	Criteria for the Deletion of An Organic Pollutant .	E-2
2.2	Evaluation	
2.2.1	Introduction	E-2
2.2.2	Criterion 1	E-3
2.2.3	Criterion 2	E-4
2.2.4	Criterion 3	E-5
2.2.4.1	Land Application Comparison	E-6
2.2.4.2	Surface Disposal Comparison	E-11
2.3	Evaluation results	E-12
2.4	Conclusions	
2.4.1	Land application	E-14
2.4.2	Surface disposal	E-16
3.	INORGANIC POLLUTANTS - SURFACE DISPOSAL	
3.1	Introduction	E-17
3.2	Evaluation - Sewage Sludge	E-17
3.3	Evaluation - Domestic Septage	E-18
3.4	Conclusions	
3.4.1	Sewage Sludge	E-20
3.4.2	Domestic Septage	E-20

ATTACHMENTS

A - Revised Mean Application Rates for Land Application .	E-21
B - Summary Statistics for EPA's Study on the Quality of Domestic Septage	E-25

SECTION ONE

INTRODUCTION

On February 6, 1989, the U.S. Environmental Protection Agency (EPA) proposed Standards for the Use or Disposal of Sewage Sludge (40 CFR Part 503) in the Federal Register (54 FR 5746). Included in those standards were pollutant limits for different sewage sludge use or disposal practices.

Several commenters on the proposed Standards for the Use or Disposal of Sewage Sludge recommended that some of the organic pollutants for which pollutant limits were proposed be deleted from the final standards. The main reason for this recommendation was that the pollutants are either banned or restricted for use in the United States.

Because of the comments received on the proposal, EPA decided to evaluate all of the organic pollutants in the proposed Part 503 standards for land application of sewage sludge and for placement of sewage sludge on a surface disposal site to determine whether to delete any of those pollutants from the final Part 503 standards. This paper discusses the criteria the Agency used to evaluate each organic pollutant; presents the results of the evaluations; and provides the Agency's conclusion about deleting organic pollutants from the final Part 503 standards.

The Agency also evaluated the inorganic pollutants for surface disposal for deletion from the final Part 503 regulation. This paper presents the results of that evaluation and EPA's conclusions about deleting inorganic pollutants from the surface disposal subpart in the final Part 503 regulation.

SECTION TWO

ORGANIC POLLUTANTS - LAND APPLICATION AND SURFACE DISPOSAL

2.1 Criteria for the Deletion of An Organic Pollutant.

The Agency used three criteria to evaluate whether to delete an organic pollutant from the final Part 503 regulation. For an organic pollutant to be deleted from the regulation for a particular use or disposal practice, one of the following three criteria had to be satisfied.

1. The pollutant has been banned for use in the United States; has restricted use in the United States; or is not manufactured for use in the United States.
2. Based on the results of the National Sewage Sludge Survey (NSSS), the pollutant has a low percent detect in sewage sludge.
3. Based on data from the NSSS, the limit for an organic pollutant in the Part 503 exposure assessment by use or disposal practice is not expected to be exceeded in sewage sludge that is used or disposed.

The evaluation for each of the organic pollutants for which pollutant limits were published in the proposed Part 503 standards using the above three criteria is presented below.

2.2 Evaluation

2.2.1 Introduction

The first step in the evaluation of organic pollutants is to identify the organic pollutants for which limits were proposed in the February 6, 1989, proposal (54 FR 5746) for land application of sewage sludge and for placement of sewage sludge on a surface disposal site. These pollutants are presented below in Table 1 by use or disposal practice.

Limits for organic pollutants also were proposed in Part 503 for distribution and marketing of sewage sludge and for sewage sludge placed on a monofill. The requirements for land application and distribution and marketing are combined in the final Part 503 regulation as are the requirements for placement of sewage sludge on a monofill and placement of sewage sludge on a surface disposal site. For this reason, the organic pollutants presented below for land application include the organic pollutants in the proposal for distribution and marketing and the organic pollutants for surface disposal include the organic pollutants in the proposal for a monofill.

TABLE 1 - PART 503 ORGANIC POLLUTANTS BY USE OR DISPOSAL PRACTICE

<u>Pollutant</u>	<u>Use or Disposal Practice</u>	
	<u>LA</u>	<u>SD</u>
Aldrin/dieldrin (total)	X	
Benzene		X
Benzo(a)pyrene	X	X
Bis(2-ethylhexyl)phthalate		X
Chlordane	X	X
DDT/DDE/DDD (total)	X	X
Heptachlor	X	
Hexachlorobenzene	X	
Hexachlorobutadiene	X	
Lindane	X	X
N-Nitrosodimethylamine	X	X
Polychlorinated biphenyls	X	X
Toxaphene	X	X
Trichloroethylene	X	X

LA - land application

SD - surface disposal

The next step is to evaluate each of the organic pollutants using the above three criteria.

2.2.2 Criterion 1

The organic pollutants listed in Table 2 have been banned for use in the United States; have restricted uses in the United States; or are not manufactured for use in the United States.

TABLE 2 - ORGANIC POLLUTANTS THAT HAVE BEEN BANNED, HAVE RESTRICTED USE, OR ARE NOT MANUFACTURED

<u>Pollutant</u>	<u>Reference</u>
Aldrin/dieldrin (total)	*
Chlordane	*
DDT/DDE/DDD (total)	*
Heptachlor	*
Lindane	*
N-Nitrosodimethylamine	**
Polychlorinated biphenyls	40 CFR Part 761
Toxaphene	*

* See "Suspended, Cancelled, and Restricted Pesticides, 20T-1002, U.S. Environmental Protection Agency, February 1990.

** See "1992 Directory of Chemical Producers", SRI International, Menlo Par, California, 1992.

These eight pollutants satisfy the first criterion for deletion of an organic pollutant from the final Part 503 standards for land application of sewage sludge and for placement of sewage sludge on an active sewage sludge unit.

2.2.3 Criterion 2

The percent detect from the National Sewage Sludge Survey (NSSS) for each of the organic pollutants in the proposed Part 503 standards for land application of sewage sludge and for placement of sewage sludge on an active sewage sludge unit is presented in Table 3.

TABLE 3 - PERCENT DETECT FOR ORGANIC POLLUTANTS

Pollutant	Number of POTWs	Percent Detect*
Aldrin/dieldrin (total)	177	8
Benzene	178	0
Benzo(a)pyrene	178	3
Bis(2-ethylhexyl)phthalate	178	63
Chlordane	177	0
DDT/DDE/DDD (total)	177	3
Heptachlor	177	0
Hexachlorobenzene	178	0
Hexachlorobutadiene	178	0
Lindane	177	0
N-Nitrosodimethylamine	178	0
Polychlorinated biphenyls	177	19
Toxaphene	177	0
Trichloroethylene	178	1

* Estimated percent detect in sewage sludge used or disposed at publicly owned treatment works nationwide. From "Statistical Support Documentation for the 40 CFR Part 503 Final Standards for the Use or Disposal of Sewage Sludge", Volume I, U.S. Environmental Protection Agency, Washington, D.C., November 11, 1992.

A review of the above information indicates that all of the pollutants, except aldrin/dieldrin (total), bis(2-ethylhexyl)phthalate, and polychlorinated biphenyls (PCBs), satisfy Criteria 2 for the deletion of an organic pollutant from the final Part 503 standards because the pollutants have a low percentage of detection (i.e., five percent or less) nationwide. Aldrin/dieldrin (total), bis(2-ethylhexyl)phthalate, and PCBs do not satisfy this criterion because they have a percent detect higher than five percent.

2.2.4 Criterion 3

For the Criterion 3 evaluation, the 99th percentile concentrations (see Table 7-11 in the report referenced in Table 4) from the NSSS were compared to the pollutant limits from the final Part 503 exposure assessment by use or disposal practice. For land application, the comparison was made by comparing annual pollutant loading rates. For surface disposal, pollutant concentrations from the final Part 503 exposure assessment were compared to the 99th percentile pollutant concentrations.

The 99th percentile concentrations from the NSSS were determined using the SM-ML procedure, except for bis(2-ethylhexyl)phthalate. For bis(2-ethylhexyl)phthalate, the MLE procedure was used to determine the 99th percentile concentration because the data for that pollutant appeared to be distributed log normally. The 99th percentile concentrations are presented in Table 4 and the comparisons using those concentrations

are presented below.

TABLE 4 - 99TH PERCENTILE CONCENTRATIONS

<u>Pollutant</u>	<u>Units</u>	<u>99th Percentile Concentration*</u>
Aldrin/dieldrin (total)	mg/kg	0.074
Benzene	mg/kg	7.0
Benzo(a)pyrene	mg/kg	43
Bis(2-ethylhexyl) phthalate	mg/kg	1000
Chlordane	mg/kg	1.8
DDT/DDE/DDD (total)	mg/kg	0.14
Heptachlor	mg/kg	0.14
Hexachlorobenzene	mg/kg	43
Hexachlorobutadiene	mg/kg	43
Lindane	mg/kg	0.18
N-Nitrosodimethylamine	mg/kg	210
Polychlorinated biphenyls	mg/kg	9.1
Toxaphene	mg/kg	7.4
Trichloroethylene	mg/kg	7.0

* From "Statistical Support Documentation for the 40 CFR, Part 503 Standards for the Use or Disposal of Sewage", Volume I, U.S. Environmental Protection Agency, Washington, D.C., November 11, 1992. Values are on dry weight basis and are reported in two significant figures.

2.2.4.1 Land Application Comparison

For the purpose of comparing annual pollutant loading rates for land application, the annual whole sludge application rates in Table 5, which are from the NSSS (see Attachment A), were used in equation (1) below with the 99th percentile concentration from the NSSS to determine the calculated annual pollutant loading rates. The comparisons of the calculated annual pollutant loading rates to the annual pollutant loading rates from the Part 503 exposure assessment are presented Tables 6 through 9.

TABLE 5 - ANNUAL WHOLE SLUDGE APPLICATION RATES

<u>Type of Land</u>	<u>Annual Whole Sludge Application Rate*</u>
Agricultural	7
Forest	26
Public contact site	18
Reclamation site	74

* Metric tons per hectare per 365 day period (dry weight basis).

$$APLR = C \times AWSAR \times 0.001$$

(1)

where,

APLR = Annual pollutant loading rate in kilograms per hectare per 365 day period.

C = pollutant concentration in milligrams per kilograms (dry weight basis).

AWSAR = Annual whole sludge application rate in metric tons per hectare per 365 day period (dry weight basis).

0.001 = A conversion factor.

Agricultural land:

TABLE 6 - COMPARISON OF ANNUAL LOADS FOR AGRICULTURAL LAND

<u>Pollutant</u>	<u>APLR (Exposure) kg/ha/365</u>	<u>APLR (NSSS) kg/ha/365</u>
Aldrin/dieldrin (total)	0.027	0.00051
Benzo(a)pyrene	0.15	0.30
Chlordane	0.86	0.012
DDT/DDE/DDD (total)	1.2	0.00098
Heptachlor	0.074	0.00098
Hexachlorobenzene	0.29	0.30
Hexachlorobutadiene	6.0	0.30
Lindane	0.84	0.0012
N-Nitrosodimethylamine	0.021	1.4
Polychlorinated biphenyls	0.046	0.063
Toxaphene	0.10	0.049
Trichloroethylene	100	0.05

The annual pollutant loading rate for benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, and PCBs calculated using the 99th percentile concentration for each pollutant from the NSSS and an annual whole sludge application rate of seven metric tons per hectare per 365 day period is greater than the annual pollutant loading rate for those pollutants from the Part 503 exposure assessment. For this reason, those pollutants do not satisfy Criterion 3 for application of sewage sludge to agricultural land.

Forest:

TABLE 7 - COMPARISON OF ANNUAL LOADS FOR FORESTS

<u>Pollutant</u>	<u>APLR (Exposure)</u> <u>kg/ha/365</u>	<u>APLR (NSSS)</u> <u>kg/ha/365</u>
Aldrin/dieldrin (total)	0.027	0.0019
Benzo(a)pyrene	0.15	1.1
Chlordane	0.86	0.046
DDT/DDE/DDD(total)	1.2	0.0036
Heptachlor	0.074	0.0036
Hexachlorobenzene	0.29	1.1
Hexachlorobutadiene	6.0	1.1
Lindane	0.84	0.0046
N-Nitrosodimethylamine	0.021	5.4
Polychlorinated biphenyls	0.046	0.23
Toxaphene	0.10	0.19
Trichloroethylene	100	0.18

The annual pollutant loading rate for benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene calculated using the 99th percentile concentration from the NSSS and an annual whole sludge application rate of 26 metric tons per hectare per 365 day period is greater than the annual pollutant loading rate for those pollutants from the Part 503 exposure assessment. For this reason, those pollutants do not satisfy Criterion 3 for application of sewage sludge to forests.

Public contact site:

TABLE 8 - COMPARISON OF ANNUAL LOADS FOR PUBLIC CONTACT SITES

<u>Pollutant</u>	<u>APLR (exposure)</u> <u>kg/ha/365</u>	<u>APLR (NSSS)</u> <u>kg/ha/365</u>
Aldrin/dieldrin (total)	0.027	0.0013
Benzo(a)pyrene	0.15	0.77
Chlordane	0.86	0.032
DDT/DDE/DDD(total)	1.2	0.0025
Heptachlor	0.074	0.0025
Hexachlorobenzene	0.29	0.77
Hexachlorobutadiene	6.0	0.77
Lindane	0.84	0.0032
N-Nitrosodimethylamine	0.021	3.7
Polychlorinated biphenyls	0.046	0.16
Toxaphene	0.10	0.12
Trichloroethylene	100	0.13

The annual pollutant loading rate for benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene calculated using the 99th percentile concentration from the NSSS and an annual whole sludge application rate of 18 metric tons per hectare per 365 day period exceeds the annual pollutant loading rate for those pollutants from the Part 503 exposure assessment. For this reason, those pollutants do not satisfy Criterion 3 for application of sewage sludge to a public contact site.

Reclamation site:

TABLE 9 - COMPARISON OF ANNUAL LOADS FOR RECLAMATION SITES

<u>Pollutant</u>	<u>APLR (Exposure)</u> <u>kg/ha/365</u>	<u>APLR (NSSS)</u> <u>kg/ha/365</u>
Aldrin/dieldrin (total)	0.027	0.0054
Benzo(a)pyrene	0.15	3.1
Chlordane	0.86	0.13
DDT/DDE/DDD(total)	1.2	0.010
Heptachlor	0.074	0.010
Hexachlorobenzene	0.29	3.1
Hexachlorobutadiene	6.0	3.1
Lindane	0.84	0.013
N-Nitrosodimethylamine	0.021	15
Polychlorinated biphenyls	0.046	0.67
Toxaphene	0.10	0.54
Trichloroethylene	100	0.51

The annual pollutant loading rates for benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene calculated using the 99th percentile concentration for each pollutant from the NSSS and an annual whole sludge application rate of 74 metric tons per hectare per 365 day period exceed the annual pollutant loading rates for those pollutants from the Part 503 exposure assessment. For this reason, those pollutants do not satisfy Criterion 3 for application of sewage sludge to a reclamation site.

Annual pollutant loading rates for organic pollutants are included in the final Part 503 exposure assessment only for land application of sewage sludge. Those rates are the same for all types of land on which sewage sludge is applied. For this reason, results of the above evaluation were combined to determine which pollutants satisfy Criterion 3 for land application of sewage sludge. When this is done, the pollutants that do not satisfy Criterion 3 for land application of sewage sludge are benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene.

Sewage sludge sold or given-away in a bag or other container for application to the land (formerly distribution and marketing):

The Part 503 exposure assessment contains limits for organic pollutants for sewage sludge sold or given-away in a bag or other container for application to the land. These limits are annual pollutant loading rates.

Sewage sludge sold or given-away in a bag or other container for application to the land may be applied to all types of land. For this reason, the annual whole sludge application rates used to calculate the annual pollutant loading rates for the above land application comparison also were used to calculate the annual pollutant loading rates for sewage sludge sold or given-away in a bag or other container for application to the land.

For the purpose of comparing annual pollutant loading rates for sewage sludge sold or given-away in a bag or other container for application to the land, the highest annual whole sludge application rate (i.e., 74 metric tons per hectare per 365 day period) from the land application comparison was used in equation (2) below along with the 99th percentile concentrations from the NSSS to calculate annual pollutant loading rates. Results of the comparison of the calculated annual pollutant loading rates to the annual pollutant loading rates for sewage sludge sold or given-away in a bag or other container for application to the land from the Part 503 exposure assessment are presented in Table 10.

$$APLR = C \times AWSAR \times 0.001 \quad (2)$$

where,

APLR = annual pollutant loading rate in kilograms per hectare per 365 day period.

C = pollutant concentration in milligrams per kilogram of sewage sludge (dry weight basis).

AWSAR = annual whole sludge application rate in metric tons per hectare per 365 day period (dry weight basis).

0.001 = a conversion factor.

TABLE 10 - COMPARISON OF ANNUAL LOADS FOR SEWAGE SLUDGE SOLD OR GIVEN AWAY IN A BAG OR OTHER CONTAINER FOR APPLICATION TO THE LAND

<u>Pollutant</u>	<u>APLR (Exposure) kg/hectare/365</u>	<u>APLR (NSSS) kg/hectare/365</u>
Aldrin/dieldrin (total)	0.027	0.0054
Benzo(a)pyrene	0.15	3.1
Chlordane	0.86	0.13
DDT/DDE/DDD (total)	1.2	0.010
Heptachlor	0.074	0.010
Hexachlorobenzene	0.29	3.1
Hexachlorobutadiene	6.0	3.1
Lindane	0.84	0.013
Polychlorinated biphenyls	0.046	0.67
Toxaphene	0.10	0.54

The annual pollutant loading rate calculated using the 99th percentile concentration for benzo(a)pyrene, hexachlorobenzene, PCBs, and toxaphene from the NSSS and an annual whole application rate of 74 metric tons per hectare per 365 day period exceeds the annual pollutant loading rate for those pollutants from the Part 503 exposure assessment. For this reason, those pollutants do not satisfy Criterion 3 for sewage sludge sold or given away in a bag or other container for application to the land.

2.2.4.2 Surface Disposal

For this disposal practice, the 99th percentile concentrations from the NSSS were compared to the Part 503 pollutant concentrations from the exposure assessment for an active sewage sludge unit without a liner and leachate collection system. This comparison is presented in Table 11.

TABLE 11 - COMPARISON OF ORGANIC POLLUTANT CONCENTRATIONS FOR SURFACE DISPOSAL

<u>Pollutant</u>	<u>Concentration*</u> <u>Exposure - mg/kg</u>	<u>Concentration</u> <u>NSSS - mg/kg</u>
Benzene	140	7.0
Benzo(a)pyrene	>100,000	43
Bis(2-ethylhexyl)phthalate	>100,000	1000
Chlordane	>100,000	1.8
DDT/DDE/DDD (total)	>100,000	0.14
Lindane	28,000	0.18
N-Nitrosodimethylamine	0.088	210
Polychlorinated biphenyls	110	9.1
Toxaphene	26,000	7.4
Trichloroethylene	9,500	7.0

* Active sewage sludge unit without a liner and leachate collection system.

N-Nitrosodimethylamine does not satisfy Criterion 3 for placement of sewage sludge on an active sewage sludge unit because the 99th percentile concentration for that pollutant from the NSSS exceeds the concentration for that pollutant from the Part 503 exposure assessment. All of the other organic pollutants for this practice satisfy Criterion 3.

2.3 Evaluation results.

Following are the results of the evaluation of the organic pollutants for which pollutant limits were published in the proposed Part 503 standards to determine which of those pollutants, if any, to delete from the final Part 503 standards:

- o Eight of the organic pollutants for which pollutant limits were published in the proposed Part 503 regulation for land application of sewage sludge and placement of sewage sludge on a surface disposal site have been banned for use in the United States; have been restricted for use in the United States; or are not manufactured in the United States. They are: aldrin/dieldrin (total), chlordane, DDT/DDE/DDD (total), heptachlor, lindane, N-Nitrosodimethylamine, polychlorinated biphenyls, and toxaphene. These pollutants satisfy Criterion 1.

- o The percent detect from the NSSS for the organic pollutants for which limits were proposed for land application of sewage sludge and placement of sewage sludge on a surface disposal site are low (i.e., five percent or less), except for aldrin/dieldrin (total), bis(2-ethylhexyl)phthalate, and polychlorinated biphenyls. All of the other organic pollutants for which limits were proposed satisfy Criterion 2.

o With the exception of benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene, the annual pollutant loading rate for the organic pollutants calculated using the 99th percentile concentration for each pollutant from the NSSS and an annual whole application rate from the NSSS is below the Part 503 exposure assessment annual pollutant loading rate for each organic pollutant for sewage sludge applied to agricultural land, forest, a public contact site, or a reclamation site. For land application of sewage sludge, benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine, PCBs, and toxaphene do not satisfy Criterion 3.

o With the exception of benzo(a)pyrene, hexachlorobenzene, PCBs, and toxaphene, the annual pollutant loading rate for the organic pollutants calculated using the 99th percentile concentration for each pollutant from the NSSS and an annual whole sludge application rate from the NSSS is below the final Part 503 exposure assessment annual pollutant loading rate for each organic pollutant for sewage sludge sold or given-away in a bag or other container for application to the land (formerly distribution and marketing). For sewage sludge sold or given away in a bag or other container, benzo(a)pyrene, hexachlorobenzene, PCBs, and toxaphene do not satisfy Criterion 3.

o With the exception of N-Nitrosodimethylamine, the 99th percentile pollutant concentration from the NSSS is below the Part 503 exposure assessment concentration for each organic pollutant in sewage sludge placed on an active sewage sludge unit without a liner and leachate collection system. For this practice, N-Nitrosodimethylamine does not satisfy Criterion 3.

2.4 Conclusions

Based on the results of the above evaluations, the Agency is deleting organic pollutants from the final Part 503 regulation, as indicated below, for the appropriate use or disposal practice. EPA concluded that because those organic pollutants satisfy one of the three criteria discussed above, public health and the environment are protected from the reasonably anticipated adverse effects of the organic pollutants in sewage sludge without establishing limits for the pollutants in the final Part 503 regulation.

2.4.1 Application to agricultural land, forest, a public contact site, or a reclamation site - pollutants deleted:

<u>Pollutant</u>	<u>Criteria Met</u>
Aldrin/dieldrin (total)	1 and 3
Benzo(a)pyrene	2
Chlordane	1, 2, and 3
DDT/DDE/DDD (total)	1, 2, and 3
Heptachlor	1, 2, and 3
Hexachlorobenzene	2
Hexachlorobutadiene	2 and 3
Lindane	1, 2, and 3
N-Nitrosodimethylamine	1 and 2
Polychlorinated biphenyls	1
Toxaphene	1 and 2
Trichloroethylene	2 and 3

Organic pollutant remaining: none.

Sewage sludge sold or given-away in a bag or other container for application to the land (formerly distribution and marketing) - pollutants deleted:

<u>Pollutant</u>	<u>Criteria Met</u>
Aldrin/dieldrin (total)	1 and 3
Benzo(a)pyrene	2
Chlordane	1, 2, and 3
DDT/DDE/DDE (total)	1, 2, and 3
Heptachlor	1, 2, and 3
Hexachlorobenzene	2
Hexchlorobutadiene	2 and 3
Lindane	1, 2, and 3
Polychlorinated biphenyls	1
Toxaphene	1 and 2

Organic pollutants remaining: none

As indicated above, PCBs were deleted from the final Part 503 regulation for land application because Criterion 1 is satisfied. PCBs are restricted for use in the United States. They can be used only in closed systems and the disposal of PCBs is closely regulated under the Toxic Substances Control Act (40 CFR Part 761).

Based on the results of the National Sewage Sludge Survey (NSSS), PCBs did not satisfy Criterion 2. PCBs are estimated to be detected in sewage sludge that is used or disposed at 19 percent of the publicly owned treatment works nationwide. To satisfy Criterion 2, the percent detect had to be five percent or less.

PCBs also did not satisfy Criterion 3. If PCBs had been

regulated, the pollutant limit for PCBs based on results of the exposure assessment would be 0.046 kilograms per hectare per 365 day period. The annual pollutant loading rate (APLR) delivered to each hectare of land assuming a concentration of PCBs in the sewage sludge equal to the 99th percentile concentration from the NSSS (i.e., 9.1 milligrams per kilogram) and an annual whole sludge application rate of 7, 18, 26, and 74 metric tons per hectare for agricultural land, forest, a public contact site, and a reclamation site, respectively, would be 0.063, 0.16, 0.23, and 0.67 kilograms per hectare, respectively.

For application to agricultural land, which is by far the most widely used land for application of sewage sludge, the above APLR calculated using the 99th percentile PCB concentration is higher than the pollutant limit for PCBs that would have been in the final Part 503 regulation by only 37 percent. The APLRs for the other types of land are higher than the potential Part 503 APLR by larger factors. However, this is mitigated by the fact that sewage sludge only is applied to forest, a public contact site, or a reclamation site at most every three to five years. In the case of a reclamation site, sewage sludge is applied to the site at most three times during the period that the land is a reclamation site.

Another factor that mitigates the calculated APLRs is the use of the 99th percentile concentration for PCBs from the NSSS to calculate the APLRs. This concentration represents, to a large extent, outlier values for PCBs and, therefore, is conservative. If the more reasonable worst case 90th percentile concentration for PCBs (i.e., 1.9 milligrams per kilogram) is used to calculate the APLRs, the annual amounts delivered to a hectare of land are 0.013, 0.034, 0.049, and 0.14 kilograms for agricultural land, forest, a public contact site, and reclamation site, respectively. In this case, the calculated APLRs for agricultural land and forest satisfy Criterion 3, the APLR for a public contact site is only slightly higher than the exposure assessment value for PCBs (i.e., 0.046 kilograms per hectare per 365 day period), and the APLR for a reclamation site does not satisfy Criterion 3.

EPA is committed to re-evaluate the decision not to regulate PCBs in the final Part 503 regulation during the next review of the regulation (i.e., Round II). EPA expects the concentration of PCBs in sewage sludge to continue to decrease. In addition, EPA will re-evaluate the toxicity of PCB congeners through use of a toxicity equivalent factor system. Both of these factors will be considered in Round II.

2.4.2 Surface disposal - pollutant deleted:

Pollutant	Criteria Met
Benzene	2 and 3
Benzo(a)pyrene	2 and 3
Bis(2-ethylhexyl)phthalate	3
Chlordane	1, 2, and 3
DDT/DDE/DDD (total)	1, 2, and 3
Lindane	1, 2, and 3
N-Nitrosodimethylamine	1 and 2
Polychlorinated biphenyls	1 and 3
Toxaphene	1, 2, and 3
Trichloroethylene	2 and 3

Organic pollutants remaining: none

SECTION THREE

INORGANIC POLLUTANTS - SURFACE DISPOSAL

3.1 Introduction

After reviewing results of the exposure assessment for surface disposal, the Agency decided to evaluate the inorganic pollutants to determine whether to include limits in the final Part 503 regulation for all of the inorganic pollutants for which limits were included in the proposed Part 503 regulation. This evaluation was done for both sewage sludge and domestic septage. Results the evaluations and the Agency's conclusions based on those results are presented below.

3.2 Evaluation - Sewage Sludge

The evaluation to determine whether to include limits for inorganic pollutants in sewage sludge placed on an active sewage sludge unit in the final Part 503 regulation consisted of comparing the limits from the Part 503 exposure assessment to the 99th percentile concentration for a pollutant from the NSSS. Results of this comparison are present in Table 12.

TABLE 12 - COMPARISON OF INORGANIC POLLUTANT CONCENTRATIONS FOR SEWAGE SLUDGE

Pollutant	Concentration ¹ (mg/kg)	Concentration ² (mg/kg)	Concentration ³ (mg/kg)
Arsenic	75	73	>100,000
Cadmium	85	>100,000	>100,000
Chromium	1200	600	>100,000
Copper	4300	46,000	>100,000
Lead	840	>100,000	>100,000
Mercury	58	>100,000	>100,000
Nickel	420	690	>100,000

- 1 - From "Statistical Support Documentation for the 40 CFR, Part 503 Final Standards for the Use or Disposal of Sewage Sludge, Volume I, U.S. Environmental Protection Agency, Washington, D.C., November 11, 1992. Pollutant concentrations are dry weight 99th percentile concentrations.
- 2 - From Part 503 exposure assessment for an active sewage sludge unit without a liner and leachate collection system (dry weight basis) - see technical support document for the Part 503 surface disposal requirements.
- 3 - From Part 503 exposure assessment for an active sewage sludge unit with a liner and leachate collection system (dry weight basis) - see technical support document for the Part 503 surface disposal requirements.

Results of the above comparison indicate that the 99th percentile pollutant concentrations are much lower than the Part 503 exposure assessment concentrations for an active sewage sludge unit without a liner and leachate collection system, except for arsenic, chromium, and nickel. In the case of arsenic, chromium, and nickel, the 99th percentile concentration is either higher than or very close to the exposure assessment concentrations for those pollutants.

The above results also indicate that the 99th percentile pollutant concentrations are much lower than the Part 503 exposure assessment concentrations for an active sewage sludge unit with a liner and leachate collection system. In this case, all of the 99th percentile concentrations are at least an order of magnitude lower than the exposure assessment concentrations.

3.3 Evaluation - Domestic Septage

The evaluation to determine whether to include limits in the final Part 503 regulation for inorganic pollutants in domestic septage placed on an active sewage sludge unit consisted of comparing the limit from the Part 503 exposure assessment for sewage sludge placed on an active sewage sludge unit to the 98th percentile concentration for a pollutant in domestic septage (see

Attachment B). Results of this comparison are presented in Table 13.

TABLE 13 - COMPARISON OF INORGANIC POLLUTANT CONCENTRATIONS FOR DOMESTIC SEPTAGE

Pollutant	Concentration ¹ (mg/kg)	Concentration ² (mg/kg)	Concentration ³ (mg/kg)
Arsenic	30 ⁴	73	>100,000
Cadmium	25	>100,000	>100,000
Chromium	110	600	>100,000
Copper	2600	46,000	>100,000
Lead	100	>100,000	>100,000
Mercury	0.91	>100,000	>100,000
Nickel	50	690	>100,000

- 1 - Concentration on a dry weight basis (see page 26 in Attachment B).
- 2 - From Part 503 exposure assessment for an active sewage sludge unit without a liner and leachate collection system (dry weight basis) - see the technical support document for the Part 503 surface disposal requirements.
- 3 - From Part 503 exposure assessment for an active sewage sludge unit with a liner and leachate collection system (dry weight basis) - see the technical support document for the Part 503 surface disposal requirements.
- 4 - Concentration is the minimum level value (i.e., highest detection limit value) because arsenic was not detected in any of the collected domestic septage samples.

Results of the above comparison indicate that the 98th percentile pollutant concentrations are lower than the Part 503 exposure assessment concentrations for sewage sludge placed on an active sewage sludge unit both with and without a liner and leachate collection system. The 98th percentile concentration that is the closest to the Part 503 concentration is the value for arsenic when compared to the Part 503 exposure assessment concentration for an active sewage sludge unit without a liner and leachate collection system. As indicated in a footnote above, arsenic was not detected in any of the domestic septage samples collected and analyzed. The concentration for arsenic in the table is the minimum level value (i.e., the highest detection limit) for arsenic in the domestic septage samples collected and analyzed.

3.4 Conclusions

3.4.1 Sewage Sludge

After comparing the 99th percentile concentrations to the Part 503 exposure assessment concentrations for an active sewage sludge unit without a liner and leachate collection system, the Agency concluded that limits only should be included in the final Part 503 regulation for arsenic, chromium, and nickel. Limits are not needed in the final regulation to protect public health and the environment from cadmium, copper, lead, and mercury in the sewage sludge because the 99th percentile concentration is much lower than the exposure assessment concentration for each of those pollutants. In this case, the concentration of cadmium, copper, lead, and mercury in the sewage sludge is not expected to exceed the exposure assessment concentration for those pollutants. Consequently, there are no pollutant limits for cadmium, copper, lead, and mercury in the final Part 503 regulation for an active sewage sludge without a liner and leachate collection system.

The Agency also concluded that no limits are needed in the final Part 503 regulation for inorganic pollutants in sewage sludge placed on an active sewage sludge unit with a liner and leachate collection system to protect public health and the environment because the 99th percentile concentrations are much lower than the exposure assessment concentrations for the inorganic pollutants. The concentration of each of the inorganic pollutants in sewage sludge is not expected to exceed the exposure assessment concentration for the pollutant. Consequently, there are no pollutant limits in the final Part 503 regulation for sewage sludge placed on an active sewage sludge unit with a liner and leachate collection system.

3.4.2 Domestic Septage

After comparing the 98th percentile domestic septage concentrations to the Part 503 exposure assessment concentrations for an active sewage sludge unit both with and without a liner and leachate collection, the Agency concluded that limits are not needed in the final Part 503 regulation to protect public health and the environment from the reasonably anticipated of arsenic, cadmium, chromium, copper, lead, mercury, and nickel in domestic septage placed on an active sewage sludge unit because the 98th percentile concentrations are lower than the Part 503 exposure assessment concentrations for those pollutants. In this case, the concentration of each of those pollutants is not expected to exceed the exposure assessment concentration for each pollutant. Consequently, there are no limits for inorganic pollutants in the final Part 503 regulation for domestic septage placed on either an active sewage sludge without a liner and leachate collection system or an active sewage sludge unit with a liner and leachate collection system.

MEMORANDUM

Date: November 10, 1992
To: Bob Southworth, EPA
From: Anne Jones and Matt Murphy, ERG
Re: Revised Mean Application Rates for Land Application

=====

We have calculated weighted mean application rates for agricultural land application, land application to forest sites and public contact sites, and land reclamation. The following methodology was used to derive these numbers.

First, we used the analytical survey rather than the larger questionnaire survey for the following reason. A question on numbers of applications was critical to the calculation of application rates. However, respondents frequently, and fairly consistently, misinterpreted this question. We made corrections (based on call backs) to the question on number of applications, as well as to other questions that affected application rates, to many of the analytical survey observations. Thus a larger proportion of the analytical survey had application rates based on corrected data than the questionnaire survey. Because we had more confidence in a greater proportion of data in the analytical questionnaire, we preferred to use this questionnaire.

Second, because of some remaining problems with the question on number of applications we limited the number of applications to 10, that is, we allowed this number to range up to 10, but where any number exceeded 10, it was set to 10. This was felt to be a very conservatively high estimate of numbers of applications. We feel that, if anything, this assumption would tend to somewhat overstate actual application rates in most cases.

Finally, we deleted one observation, which was a POTW practicing land reclamation. This POTW was applying sewage sludge at over 1,600 dmt/ha. The sewage sludge fails ceiling concentrations, but even if it passed, it is highly unlikely that this application rate would be allowed under Subpart B. The mean application rate shown in the following tables reflects the deletion of this observation.

We then ran the Univariate Procedure in SAS to obtain the weighted means discussed below and presented in the attached tables.

The results of this analysis are as follows: agricultural rates average about 7 dmt/ha; rates at forest sites average 26 dmt/ha; rates at public contact sites average 19 dmt/ha; and rates at reclamation sites average 74 dmt/ha, as shown in the attached tables.

NEWUSE=AG

Univariate Procedure

Variable=MTHAYR
Weight= ANAL_WT

Moments

N	87	Sum Wgts	3691
Mean	6.768121	Sum	24981.14
Std Dev	104.9951	Variance	11023.97
Skewness		Kurtosis	
USS	1117138	CSS	948081.1
CV	1551.318	Std Mean	11.25665
T:Mean=0	0.801255	Pr> T	0.5493
Num ^= 0	87	Num > 0	87
M(Sign)	43.5	Pr>= M	0.0001
Sgn Rank	1914	Pr>= S	0.0001

Quantiles(Def=5)

100% Max	290	99%	290
75% Q3	16.3666	95%	53.4717
50% Med	7.53312	90%	43.719
25% Q1	1.61424	10%	0.13452
0% Min	0.026904	5%	0.035872
Range	289.9731	1%	0.026904
Q3-Q1	14.75236		
Mode	0.026904		

Extremes

Lowest	Obs	Highest	Obs
0.026904	40	53.4717	19
0.026904	39	58.5162	51
0.026904	73	61.2066	9
0.035872	72	75.3312	50
0.035872	71	290	25

Missing Value	2
Count	
% Count/Nobs	2.25

The SAS System

11:50 Tuesday, November 10, 1992 3

NEWUSE=FOR

Univariate Procedure

Variable=MTHAYR
Weight= ANAL_WT

Moments

N	2	Sum Wgts	12
Mean	26.06325	Sum	312.759
Std Dev	26.21199	Variance	687.0685
Skewness		Kurtosis	
USS	8838.584	CSS	687.0685
CV	100.5707	Std Mean	18.53468
T:Mean=0	1.406189	Pr> T	0.3935
Num ^= 0	2	Num > 0	2
M(Sign)	1	Pr>= M	0.5000
Sgn Rank	1.5	Pr>= S	0.5000

Quantiles(Def=5)

100% Max	33.63	99%	33.63
75% Q3	33.63	95%	33.63
50% Med	26.06325	90%	33.63
25% Q1	18.4965	10%	18.4965
0% Min	18.4965	5%	18.4965
Range	15.1335	1%	18.4965
Q3-Q1	15.1335		
Mode	18.4965		

Extremes

Lowest	Obs	Highest	Obs
18.4965	2		
33.63	1		
		18.4965	2
		33.63	1

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Extremes		
west	Obs	Obs
18114	11	102.011
0356	10	116.584
7279	9	124.8552
0055	8	230.2534
1532	4	246.184
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lowest	Obs	Highest	Obs
45	7	65.9148	3
45	6	65.9148	4
.9148	5	65.9148	5
.9148	4	100.89	2
.9148	3	420.7113	1



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

NOV 6 1992

OFFICE OF
WATER

MEMORANDUM

Subject: Summary Statistics for EPA's Study on the Quality of Domestic Septage

From: Charles E. White, Statistician *[Signature]*
Statistical Analysis Section

To: Alan Rubin, Chief
Sludge Risk Assessment Branch

Through: Henry D. Kahn, Chief *[Signature]*
Statistical Analysis Section

At your request, I will present and document summary statistics based on EPA's Study on the Quality of Domestic Septage. These summary statistics will include basic statistics on pollutants of concern, other requested pollutants, and the estimated relationship between Total Kjeldahl Nitrogen and Ammonia. EPA's Study on the Quality of Domestic Septage (1991) was conducted in order to support the development of hydraulic loading rates for the land application of domestic septage under the 40 CFR Part 503 Final Rule for Sewage Sludge Use or Disposal. This loading rate is intended to be a protective and affordable method for regulating the beneficial reuse of septage. Development of the loading rate itself will not be discussed in this memo.

Results

There are two basic results from these analyses. First, truckloads of domestic septage are not expected to contain pollutant concentrations as high as could be found in sewage sludge used or disposed from Publicly Owned Treatment Works that practice secondary or better wastewater treatment. Second, Total Kjeldahl Nitrogen is found to be approximately 43% Ammonia in wet domestic septage.

Data

Nine trucks delivering domestic septage to the Madison Metropolitan Sewerage District (MMSD) in Madison, Wisconsin were each sampled once. As septage was being discharged, a grab sample was collected and delivered to the MMSD lab for splitting, labeling, icing, and shipping to appropriate labs under contract to the EPA. Each

independent sample was physically analyzed for 324 pollutants. Only data regarding pollutants of concern and some data for pollutants that are also micro-nutrients will be considered in this report.

Physical Analytical Procedures

Physical analytical methods used here are the same as those used for the National Sewage Sludge Survey (NSSS), though some pollutants are reported differently. Individual PCB aroclors were reported in the NSSS; total PCB aroclors are reported here. Aldrin and Dieldrin were reported separately in the NSSS; the totals for Aldrin and Dieldrin are reported here. Total Chlordane is reported in the NSSS; the alpha and gamma portions of chlordane are reported here. DDT, DDS, and DDD are reported separately in the NSSS; totals for DDT, DDS, and DDD are reported here. Lindane is reported in the NSSS; Lindane (Gamma-BHC) is reported here.

Some pollutant concentrations were not measured above the Minimum Level for the particular pollutant. Minimum Levels are a form of "detection limit" used in physical analytical methods developed for the Office of Science and Technology. Under contract, each contractor lab must demonstrate that it is able to achieve the Minimum Levels stated for the particular EPA method to be used. In general, a Minimum Level is defined as the lowest concentration at which the physical analytical process can be reliably calibrated. Pollutant concentrations not measured above the Minimum Level for a particular pollutant are not reported; the Minimum Level is reported instead.

Statistical Methods for Basic Summary Statistics

Statistical analysis methods were primarily selected to estimate a concentration level for each pollutant such that, under certain assumptions, "most" septage concentrations for a particular pollutant will be below it's respective level, i.e., we are primarily estimating percentiles. These methods will also be used to characterize both wet and dry weight pollutant concentration measurements, mixed with "detection limits." Substitution and Maximum Likelihood Methods will be used to estimate summary statistics. One overall assumption of this study is that residential septage samples across the country follow approximately the same probability distributions for pollutant concentrations as those distributions found in the area around Madison, Wisconsin. Additional statistical assumptions are discussed in the section on the Substitution Method, in the section on the Maximum Likelihood Method for estimating summary statistics in the presence of censored, or "non-detect," data and in the section on estimating the relationship between Ammonia and Total Kjeldahl Nitrogen.

Dry Weight Conversion

Physical analyses were conducted on liquid septage samples. However, both because pollutants are assumed to be concentrated in the solid phase of the septage sample and

because pollutants were reported this way in the NSSS, a dry weight conversion is also used in presentation of these data. More detailed discussion of the reasons for dry weight conversion and analyses in support of this practice are presented in the *Statistical Support Document for the 40 CFR Part 503 Final Rule for Sewage Sludge Use or Disposal*. Conversion of a concentration reported in ug/l is illustrated below:

Let: Pollutant Concentration for Sample $i = x_i$ $\mu\text{g/l}$
 Solids Concentration for Sample $i = y_i$ mg/l

$$\begin{aligned} \text{Dry Weight Pollutant Concentration in } \mu\text{g/kg} &= \frac{x_i \mu\text{g/l}}{y_i \text{mg/l}} \left(\frac{1,000,000 \text{ mg}}{\text{kg}} \right) \\ &= \left(\frac{1,000,000 x_i}{y_i} \right) \mu\text{g/kg} \end{aligned}$$

Substitution Methods

The substitution methods used here make no assumptions about the probability distributions of the pollutant concentration data, but they do make assumptions about the concentration of pollutants in samples where pollutants could not be measured above their "detection limit." The first of two substitution methods used assumes that pollutant concentrations, in samples where pollutants could not be measured, are at the "detection limit." The second substitution method assumes that pollutant concentrations, in samples where pollutants could not be measured, are zero. Together, these two substitution methods give a kind of upper and lower bound on non-parametric summary statistics for pollutant concentrations in septage. More detailed discussion of these methods and the reasons for their selection are presented in the *Statistical Support Document for the 40 CFR Part 503 Final Rule for Sewage Sludge Use or Disposal*.

Tables of wet weight summary statistics developed using these substitution methods are presented on pages 13 through 23 and tables of dry weight summary statistics developed using these substitution methods are presented on pages 27 through 36.

Maximum Likelihood Estimation

The maximum likelihood estimation (MLE) procedure used here assumes pollutant concentrations are approximately lognormal in probability distribution. When this assumption is true, estimates produced using this procedure will be more efficient than those produced without assumptions about probability distributions. The procedure uses sample

size, measured pollutant concentrations, and the range of possible values for "detection limit" data in order to pick optimum estimates for the log mean and log variance of a two parameter lognormal distribution. If the assumption of a lognormal distribution is not closely approximated, this procedure is expected to produce good estimates for upper percentiles while the mean and variance estimates may not be optimal.

The two parameter lognormal distribution is fully described by the log mean and log variance, or the mean and standard deviation. Any desired summary statistic can be calculated using an appropriate pair of sufficient statistics. More detailed discussion of this method and the reasons why it was selected are presented in *Statistical Support Document for the 40 CFR Part 503 Final Rule for Sewage Sludge Use or Disposal* (1992).

In order to assess the quality of the MLEs, cumulative probability distributions were plotted for both the wet and dry weight distributions. Each plot shows the estimated cumulative distribution for all three estimation methods. The substitution methods are illustrated with points for each observation. The probability plotting position for each point is determined by a ranking procedure developed by Blom. The line indicating the estimated lognormal distribution is a plot of the 10th through 90th percentiles. These plots do not indicate any obvious deviations from the assumption that the pollutant concentration data are approximately lognormal in distribution. These plots are presented in the appendix.

Tables for wet weight summary statistics are presented on pages 10 through 12 and tables for dry weight summary statistics are presented on pages 24 through 26. Pollutants measured above their sample specific Minimum Level, or "detection limit," one time or less are not included in these tables as it is not possible to obtain MLEs under those conditions.

Note that truckloads of domestic septage are not expected to contain pollutant concentrations as high as could be found in sewage sludge used or disposed from Publicly Owned Treatment Works that practice secondary or better wastewater treatment. This statement is based on the previously mentioned distributional assumptions of the MLE estimation procedure and the additional assumption that domestic septage trucks across the country have approximately the same probability distribution for pollutant concentrations as domestic septage in trucks found in the area around Madison, Wisconsin. This result is found by comparing the 98th percentile estimates from the National Sewage Sludge Survey, presented in *Statistical Support Documentation for the 40 CFR, Part 503 Final Standards for the Use or Disposal of Sewage Sludge* (1992), to 98th percentile estimates developed here for dry weight concentrations of septage.

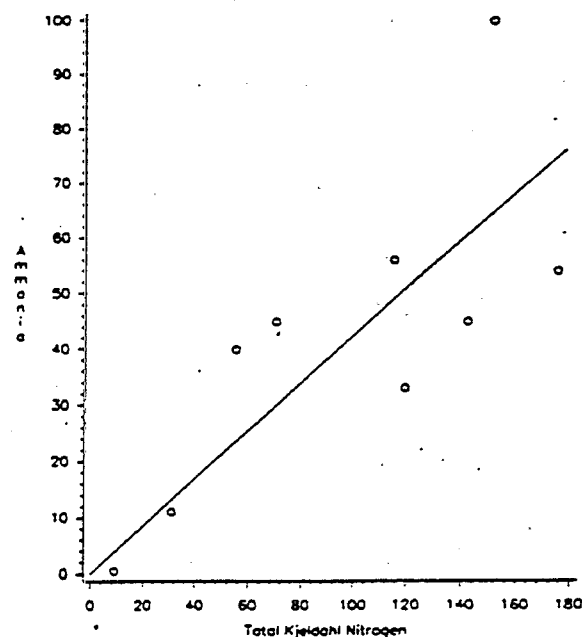
Statistical Methods for Estimating the Relationship Between Ammonia & TKN

Ammonia is the constituent of Total Kjeldahl Nitrogen (TKN) that is immediately available for plant uptake. Over time, Total Kjeldahl Nitrogen is expected to completely break down into Ammonia. The purpose of this analysis is to assist in determining an

appropriate hydraulic loading rate for domestic septage that allows sufficient nitrogen for crop growth while not allowing for so much nitrogen that crop growth would be adversely affected. The loading rate itself will be estimated in another document.

The observed relationship between the Ammonia and the Total Kjeldahl Nitrogen data indicates, as expected, that both pollutants increase together. A statistical model was fit to these data that assumes the concentration of Ammonia is zero when the concentration of TKN is zero, that the Ammonia concentration will increase in a linear fashion as TKN increases, that the Ammonia concentrations about that line are approximately normal in distribution, and that the deviations from that line are independent and identically distributed. Under these assumptions, Total Kjeldahl Nitrogen is approximately 43% Ammonia in wet domestic septage.

Relation of Total Kjeldahl Nitrogen to Ammonia:



Units are mg/l

Evaluation of Assumptions

For the assumption that the concentration of Ammonia is zero when the concentration of TKN is zero, a model was fit that estimated a non-zero constant when TKN is zero and a hypothesis test was conducted that failed to reject the hypothesis that the constant was statistically different than zero. The

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	3785.12042	3785.12042	9.806	0.0166
Error	7	2702.12438	386.01777		
C Total	8	6487.24480			
Root MSE	19.64733	R-square	0.5835		
Dep Mean	42.72000	Adj R-sq	0.5240		
C.V.	45.99095				

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T
INTERCEP	1	6.292426	13.34986889	0.471	0.6517
TKN	1	0.377705	0.12061931	3.131	0.0166

Variable	DF	Variable Label
INTERCEP	1	Intercept
TKN	1	Total Kjeldahl Nitrogen

Analysis of Variance table for this model indicates that the intercept term is not statistically significant at the 0.05 level. The significance test used is robust to many departures from assumptions.

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	20124.34510	20124.34510	57.748	0.0001
Error	8	2787.88530	348.48566		
U Total	9	22912.23040			
Root MSE		18.66777	R-square	0.8783	
Dep Mean		42.72000	Adj R-sq	0.8631	
C.V.		43.69797			

Parameter Estimates

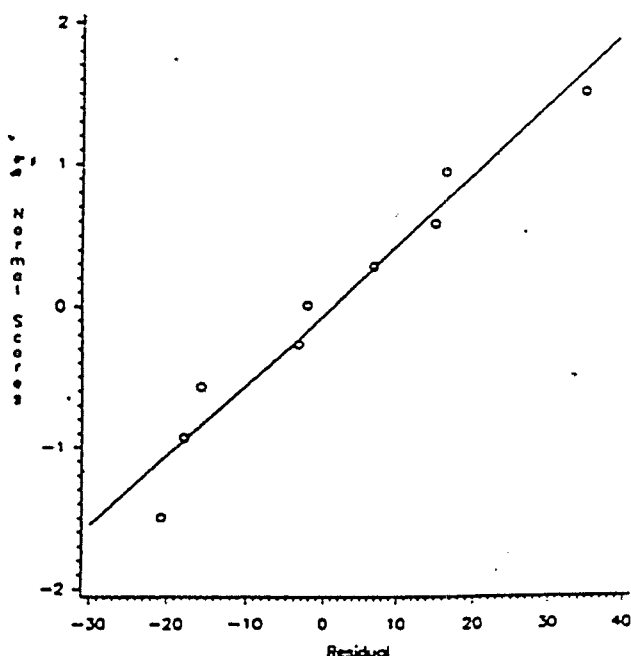
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T
TKN	1	0.427247	0.05622261	7.599	0.0001

Variable	DF	Variable Label
TKN	1	Total Kjeldahl Nitrogen

For the assumption of linearity, both the Analysis of Variance table for the model with an intercept term and for the model without an intercept term indicate that a

statistically significant linear relationship exists between Ammonia and TKN. Again, the significance test used is robust to many departures from assumptions.

Relation of Total Kjeldahl Nitrogen to Ammonia:
Normal Scores Plot of Residuals from Regression



Units are mg/l

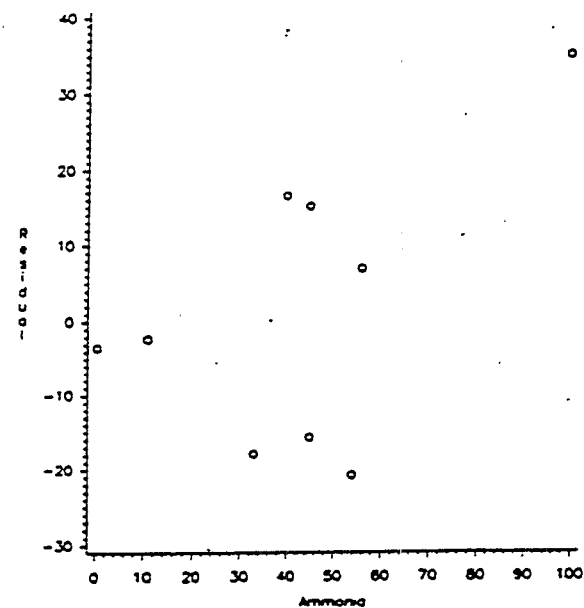
For the assumption that Ammonia concentrations about that line are approximately normal in distribution, the Shapiro-Wilk test for the normal distribution fails to reject the hypothesis that the residuals from the fitted line come from a normal distribution. Residuals are the arithmetic difference between the observed concentration of Ammonia at a particular TKN concentration and the Ammonia concentration predicted by the statistical model. Further evidence is that the plot of the residuals versus their expected position in a normal distribution, a normal scores plot, is approximately linear.

For the assumption that deviations from the line are

independent, the physical process of sampling from different truck loads of septage would tend to make the sample results independent.

For the assumption that deviations from the line are identically distributed, the plot of residuals versus observed Ammonia values does not appear to indicate strong deviation from this assumption.

Relation of Total Kjeldahl Nitrogen to Ammonia:
Residuals Versus Observed Values



Units are mg/l

References

Blom, G. (1958), *Statistical Estimates and Transformed Beta Variables*, New York: John Wiley & Sons, Inc.

USEPA (1992), *Statistical Support Documentation for the 40 CFR, Part 503 Final Standards for the Use or Disposal of Sewage Sludge*

Appendix A

Summary Statistics

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Sample Size	Non-Detect	Log Mean	Log Variance
ALDRIN/DIELDRIN (TOTAL)	UG/L	9	7	-4.872	15.2471
AMMONIA (AS N)	MG/L	9	0	3.231	2.5560
CADMIUM	UG/L	9	6	1.207	1.1385
CHROMIUM	UG/L	9	1	3.494	0.8888
COPPER	UG/L	9	0	5.373	1.8551
DDT, DDE, DDD (TOTAL)	UG/L	9	7	-2.783	6.1436
LEAD	UG/L	9	6	3.642	0.5873
LINDANE (GAMMA-BHC)	UG/L	9	7	-2.360	0.2981
MERCURY	UG/L	9	4	-1.348	2.7855
NICKEL	UG/L	9	4	3.747	0.3319
NITRATE+NITRITE (AS N)	MG/L	9	2	-1.345	1.0699
PERCENT SOLIDS	†	9	0	-0.488	2.8024
SELENIUM	UG/L	9	7	0.442	5.4810
TOTAL KJELDAHL NITROGEN	MG/L	9	0	4.284	0.9236
TOTAL PHOSPHOROUS	MG/L	9	0	2.960	1.2521
ZINC	UG/L	9	0	7.806	2.1128

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation
ALDRIN/DIELDRIN (TOTAL)	UG/L	15.7000	10700.000	32100.000	2050.0000
AMMONIA (AS N)	MG/L	90.8000	104.0000	313.0000	3.4500
CADMIUM	UG/L	5.9100	2.8700	8.6100	1.4600
CHROMIUM	UG/L	51.3000	20.5000	61.4000	1.2000
COPPER	UG/L	545.0000	422.0000	1270.0000	2.3200
DDT, DDE, DDD (TOTAL)	UG/L	1.3300	9.5900	28.8000	21.6000
LEAD	UG/L	51.2000	15.3000	45.8000	0.8940
LINDANE (GAMMA-BHC)	UG/L	0.1100	0.0215	0.0646	0.5890
MERCURY	UG/L	1.0500	1.3600	4.0800	3.9000
NICKEL	UG/L	50.0000	10.5000	31.4000	0.6270
NITRATE+NITRITE (AS N)	MG/L	0.4450	0.2050	0.6160	1.3800
PERCENT SOLIDS	%	2.4900	3.2700	9.8100	3.9300
SELENIUM	UG/L	24.1000	124.0000	373.0000	15.5000
TOTAL KJELDAHL NITROGEN	MG/L	115.0000	47.3000	142.0000	1.2300
TOTAL PHOSPHOROUS	MG/L	36.1000	19.0000	57.0000	1.5800
ZINC	UG/L	7060.0000	6350.0000	19000.000	2.7000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Median	90th Percentile	95th Percentile	98th Percentile
ALDRIN/DIELDRIN(TOTAL)	UG/L	0.0077	1.1600	4.7200	23.4000
AMMONIA (AS N)	MG/L	25.3000	197.0000	351.0000	676.0000
CADMIUM	UG/L	3.3400	13.2000	19.3000	30.0000
CHROMIUM	UG/L	32.9000	111.0000	155.0000	228.0000
COPPER	UG/L	216.0000	1240.0000	2030.0000	3540.0000
DDT, DDE, DDD (TOTAL)	UG/L	0.0619	1.4900	3.6500	10.1000
LEAD	UG/L	38.2000	102.0000	135.0000	184.0000
LINDANE(GAMMA-BHC)	UG/L	0.0944	0.1900	0.2320	0.2900
MERCURY	UG/L	0.2600	2.2200	4.0400	8.0200
NICKEL	UG/L	42.4000	88.9000	109.0000	138.0000
NITRATE+NITRITE (AS N)	MG/L	0.2610	0.9840	1.4300	2.1800
PERCENT SOLIDS	‡	0.6140	5.2800	9.6400	19.1000
SELENIUM	UG/L	1.5600	31.5000	73.2000	191.0000
TOTAL KJELDAHL NITROGEN	MG/L	72.5000	249.0000	352.0000	523.0000
TOTAL PHOSPHOROUS	MG/L	19.3000	81.3000	122.0000	192.0000
ZINC	UG/L	2460.0000	15900.000	26800.000	48700.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=ALDRIN/DIELDRIN(TOTAL) -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	0.4480	0.2660	178.0	0.1000	0.1000	2.500
SM-O	0.3610	0.2800	232.0	0.0000	0.0000	2.500

----- Pollutant=ALPHA-CHLORDANE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	0.1090	0.0093	25.6	0.1000	0.1000	0.184
SM-O	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=AMMONIA (AS N) -- Sample Size=9 -- Units=MG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	42.7000	9.4900	66.7	0.4800	45.0000	100.000
SM-O	42.7000	9.4900	66.7	0.4800	45.0000	100.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=ARSENIC -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	20.0000	0.0000	0.0	20.0000	20.0000	20.000
SM-O	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=BENZENE -- Sample Size=7 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	11.4000	1.4300	33.1	10.0000	10.0000	20.000
SM-O	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=BENZO(A)PYRENE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	11.1000	1.1100	30.0	10.0000	10.0000	20.000
SM-O	0.0000	0.0000	.	0.0000	0.0000	0.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=BERYLLIUM -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	5.0000	0.0000	0.0	5.0000	5.0000	5.000
SM-0	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=BIS(2-ETHYLHEXYL) PHTHALATE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	11.1000	1.1100	30.0	10.0000	10.0000	20.000
SM-0	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=CADMIUM -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	7.1300	1.4900	62.7	5.0000	5.0000	18.400
SM-0	3.8000	2.1700	171.0	0.0000	0.0000	18.400

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=CHROMIUM -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	46.7000	12.7000	38.1000	81.6	10.0000	33.5000	128.000
SM-0	45.6000	13.1000	39.4000	86.5	0.0000	33.5000	128.000

----- Pollutant=COPPER -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	503.0000	223.0000	669.0000	133.0	62.0000	115.0000	1850.000
SM-0	503.0000	223.0000	669.0000	133.0	62.0000	115.0000	1850.000

----- Pollutant=DDT,DDE,DDD(TOTAL) -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	0.6850	0.2810	0.8440	123.0	0.3380	0.3380	2.880
SM-0	0.4220	0.3230	0.9690	230.0	0.0000	0.0000	2.880

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=GAMMA-CHLORDANE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation	Minimum			Maximum		
	Mean	the Mean		Deviation	Variation	Minimum	Median	Maximum	
SM-ML	0.1230	0.0104	0.0313	25.4	0.1130	0.1130	0.1130	0.207	
SM-O	0.0000	0.0000	0.0000	.	0.0000	0.0000	0.0000	0.000	

----- Pollutant=HEPTACHLOR -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation	Minimum			Maximum		
	Mean	the Mean		Deviation	Variation	Minimum	Median	Maximum	
SM-ML	0.0896	0.0209	0.0626	69.9	0.0630	0.0630	0.0630	0.250	
SM-O	0.0278	0.0278	0.0833	300.0	0.0000	0.0000	0.0000	0.250	

----- Pollutant=HEXACHLOROBENZENE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation	Minimum			Maximum		
	Mean	the Mean		Deviation	Variation	Minimum	Median	Maximum	
SM-ML	11.1000	1.1100	3.3300	30.0	10.0000	10.0000	10.0000	20.000	
SM-O	0.0000	0.0000	0.0000	.	0.0000	0.0000	0.0000	0.000	

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=HEXACHLOROBUTADIENE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	11.1000	1.1100	3.3300	30.0	10.0000	10.0000	20.000
SM-O	0.0000	0.0000	0.0000	.	0.0000	0.0000	0.000

----- Pollutant=LEAD -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	63.4000	8.0800	24.2000	38.2	50.0000	50.0000	121.000
SM-O	30.1000	15.7000	47.1000	157.0	0.0000	0.0000	121.000

----- Pollutant=LINDANE(GAMMA-BHC) -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	0.1620	0.0170	0.0511	31.6	0.1250	0.1380	0.253
SM-O	0.0417	0.0295	0.0884	212.0	0.0000	0.0000	0.250

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=MERCURY -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation		Minimum Median Maximum		
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	0.8220	0.4200	1.2600	153.0	0.2000	0.3000	4.050
SM-O	0.7330	0.4380	1.3100	179.0	0.0000	0.3000	4.050

----- Pollutant=MOLYBDENUM -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation		Minimum Median Maximum		
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	10.5000	0.4890	1.4700	14.0	10.0000	10.0000	14.400
SM-O	1.6000	1.6000	4.8000	300.0	0.0000	0.0000	14.400

----- Pollutant=N-NITROSODIMETHYLAMINE -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of Standard		Coefficient of Variation		Minimum Median Maximum		
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	55.6000	5.5600	16.7000	30.0	50.0000	50.0000	100.000
SM-O	0.0000	0.0000	0.0000	.	0.0000	0.0000	0.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=NICKEL -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Coefficient of Variation	Minimum	Median	Maximum
SM-ML	54.5000	7.8300	23.5000	43.1	40.0000	41.6000
SM-0	36.7000	13.2000	39.7000	108.0	0.0000	41.6000
						105.000
						105.000

----- Pollutant=NITRATE+NITRITE (AS N) -- Sample Size=9 -- Units=MG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Coefficient of Variation	Minimum	Median	Maximum
SM-ML	0.3890	0.0964	0.2890	74.4	0.1000	0.2000
SM-0	0.3670	0.1050	0.3160	86.2	0.0000	0.2000
						0.900
						0.900

----- Pollutant=PCB(TOTAL) -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Coefficient of Variation	Minimum	Median	Maximum
SM-ML	1.9100	0.1630	0.4890	25.6	1.7500	3.220
SM-0	0.0000	0.0000	0.0000	0.0000	0.0000	0.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=PERCENT SOLIDS -- Sample Size=9 -- Units=' %' -----

Substitution Method	Standard Deviation of		Coefficient of				
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	2.2100	1.5100	4.5400	205.0	0.0653	0.6580	14.200
SM-O	2.2100	1.5100	4.5400	205.0	0.0653	0.6580	14.200

----- Pollutant=SELENIUM -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Standard Deviation of		Coefficient of				
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	20.8000	6.6400	19.9000	95.6	5.0000	5.0000	50.000
SM-O	6.9400	4.6000	13.8000	199.0	0.0000	0.0000	32.000

----- Pollutant=TOTAL KJELDAHL NITROGEN -- Sample Size=9 -- Units=MG/L -----

Substitution Method	Standard Deviation of		Coefficient of				
	Mean	the Mean	Deviation	Variation	Minimum	Median	Maximum
SM-ML	96.4000	19.2000	57.6000	59.7	9.0000	115.0000	175.000
SM-O	96.4000	19.2000	57.6000	59.7	9.0000	115.0000	175.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=TOTAL PHOSPHOROUS -- Sample Size=9 -- Units=MG/L -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	27.6000	5.7400	17.2000	62.3	1.7000	32.0000 48.000
SM-0	27.6000	5.7400	17.2000	62.3	1.7000	32.0000 48.000

----- Pollutant=TOXAPHENE -- Sample Size=9 -- Units=UG/L -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	11.3000	1.6700	5.0100	44.3	0.9100	11.4000 20.900
SM-0	0.0000	0.0000	0.0000	.	0.0000	0.0000 0.000

----- Pollutant=TRICHLOROETHENE -- Sample Size=7 -- Units=UG/L -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	11.4000	1.4300	3.7800	33.1	10.0000	10.0000 20.000
SM-0	0.0000	0.0000	0.0000	.	0.0000	0.0000 0.000

Wet Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=ZINC -- Sample Size=9 -- Units=UG/L -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	5300.0000	2420.0000	7270.0000	137.0	182.0000	3190.0000	23800.000
SM-O	5300.0000	2420.0000	7270.0000	137.0	182.0000	3190.0000	23800.000

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Sample Size	Non-Detect	Log Mean	Log Variance
ALDRIN/DIELDRIN (TOTAL)	UG/KG	9	7	0.741	8.92238
AMMONIA (AS N)	MG/KG	9	0	8.325	3.90825
CADMIUM	MG/KG	9	6	-1.766	5.86238
CHROMIUM	MG/KG	9	1	1.542	2.39400
COPPER	MG/KG	9	0	3.559	4.39988
DDT, DDE, DDD (TOTAL)	UG/KG	9	7	1.665	7.27425
LEAD	MG/KG	9	6	0.561	3.87225
LINDANE (GAMMA-BHC)	UG/KG	9	7	0.967	2.14650
MERCURY	MG/KG	9	4	-3.571	2.86875
NICKEL	MG/KG	9	4	1.330	1.57612
NITRATE+NITRITE (AS N)	MG/KG	9	2	3.522	0.82463
PERCENT SOLIDS	%	9	0	-0.488	2.80237
SELENIUM	MG/KG	9	7	-2.098	6.97725
TOTAL KJELDAHL NITROGEN	MG/KG	9	0	9.378	2.81813
TOTAL PHOSPHOROUS	MG/KG	9	0	8.054	1.42312
ZINC	MG/KG	9	0	5.992	1.05525

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation
ALDRIN/DIELDRIN (TOTAL)	UG/KG	182.0000	5240.0000	15700.000	86.6000
AMMONIA (AS N)	MG/KG	29100.000	67800.000	203000.00	6.9900
CADMIUM	MG/KG	3.2100	20.0000	60.0000	18.7000
CHROMIUM	MG/KG	15.5000	16.3000	48.8000	3.1600
COPPER	MG/KG	317.0000	948.0000	2840.0000	8.9700
DDT, DDE, DDD (TOTAL)	UG/KG	201.0000	2540.0000	7620.0000	38.0000
LEAD	MG/KG	12.1000	27.8000	83.3000	6.8600
LINDANE (GAMMA-BHC)	UG/KG	7.6900	7.0500	21.1000	2.7500
MERCURY	MG/KG	0.1180	0.1600	0.4810	4.0800
NICKEL	MG/KG	8.3200	5.4300	16.3000	1.9600
NITRATE+NITRITE (AS N)	MG/KG	51.1000	19.3000	57.9000	1.1300
PERCENT SOLIDS	%	2.4900	3.2700	9.8100	3.9300
SELENIUM	MG/KG	4.0200	43.8000	131.0000	32.7000
TOTAL KJELDAHL NITROGEN	MG/KG	48400.000	64000.000	192000.00	3.9700
TOTAL PHOSPHOROUS	MG/KG	6410.0000	3790.0000	11400.000	1.7700
ZINC	MG/KG	678.0000	309.0000	928.0000	1.3700

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Maximum Likelihood Estimation

Pollutant	Units	Median	90th Percentile	95th Percentile	98th Percentile
ALDRIN/DIELDRIN(TOTAL)	UG/KG	2.1000	97.4000	286.0000	972.0000
AMMONIA (AS N)	MG/KG	4130.0000	52300.0000	107000.00	240000.00
CADMIUM	MG/KG	0.1710	3.8400	9.1800	24.8000
CHROMIUM	MG/KG	4.6700	34.1000	59.6000	112.0000
COPPER	MG/KG	35.1000	520.0000	1110.0000	2620.0000
DDT, DDE, DDD(TOTAL)	UG/KG	5.2900	169.0000	447.0000	1350.0000
LEAD	MG/KG	1.7500	22.0000	44.6000	100.0000
LINDANE(GAMMA-BHC)	UG/KG	2.6300	17.3000	29.3000	53.4000
MERCURY	MG/KG	0.0281	0.2480	0.4560	0.9140
NICKEL	MG/KG	3.7800	19.0000	29.8000	49.9000
NITRATE+NITRITE (AS N)	MG/KG	33.9000	109.0000	151.0000	219.0000
PERCENT SOLIDS	%	0.6140	5.2800	9.6400	19.1000
SELENIUM	MG/KG	0.1230	3.6600	9.4600	27.9000
TOTAL KJELDAHL NITROGEN	MG/KG	11800.000	102000.00	187000.00	372000.00
TOTAL PHOSPHOROUS	MG/KG	3150.0000	14600.000	22400.000	36500.000
ZINC	MG/KG	400.0000	1500.0000	2170.0000	3300.0000

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=ALDRIN/DIELDRIN(TOTAL) -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	77.200	36.300	109.000	141.0	8.55000	17.6000	325.00
SM-O	38.000	35.900	108.000	283.0	0.00000	0.0000	325.00

----- Pollutant=ALPHA-CHLORDANE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	44.100	19.500	58.500	133.0	0.70400	15.2000	153.00
SM-O	0.000	0.000	0.000	.	0.00000	0.0000	0.00

----- Pollutant=AMMONIA (AS N) -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	12700.000	6390.000	19200.000	151.0	77.50000	8210.0000	61300.00
SM-O	12700.000	6390.000	19200.000	151.0	77.50000	8210.0000	61300.00

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=ARSENIC -- Sample Size=9 -- Units=MG/KG -----									
Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum			
SM-ML	8.710	3.920	135.0	0.14100	3.0400	30.60			
SM-0	0.000	0.000	.	0.00000	0.0000	0.00			

----- Pollutant=BENZENE -- Sample Size=7 -- Units=UG/KG -----									
Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum			
SM-ML	1540.000	519.000	89.1	70.40000	1080.0000	4330.00			
SM-0	0.000	0.000	.	0.00000	0.0000	0.00			

----- Pollutant=BENZO(A)PYRENE -- Sample Size=9 -- Units=UG/KG -----									
Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum			
SM-ML	4420.000	1950.000	132.0	70.40000	1520.0000	15300.00			
SM-0	0.000	0.000	.	0.00000	0.0000	0.00			

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=BERYLLIUM -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	2.180	0.981	2.940	135.0	0.03520	0.7600	7.66
SM-O	0.000	0.000	0.000	.	0.00000	0.0000	0.00

----- Pollutant=BIS(2-ETHYLHEXYL) PHTHALATE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	4420.000	1950.000	5840.000	132.0	70.40000	1520.0000	15300.00
SM-O	0.000	0.000	0.000	.	0.00000	0.0000	0.00

----- Pollutant=CADMIUM -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	2.430	0.954	2.860	118.0	0.03520	0.9950	7.66
SM-O	0.632	0.349	1.050	166.0	0.00000	0.0000	2.77

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=CHROMIUM -- Sample Size=9 -- Units=MG/KG -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	10.900	3.640	10.900	100.0	0.22600	7.6300 35.30
SM-O	9.360	3.800	11.400	122.0	0.00000	6.9200 35.30

----- Pollutant=COPPER -- Sample Size=9 -- Units=MG/KG -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	113.000	40.900	123.000	108.0	0.81000	105.0000 328.00
SM-O	113.000	40.900	123.000	108.0	0.81000	105.0000 328.00

----- Pollutant=DDT,DDE,DDD(TOTAL) -- Sample Size=9 -- Units=UG/KG -----						
Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median Maximum
SM-ML	176.000	64.500	194.000	110.0	2.38000	69.3000 518.00
SM-O	33.800	28.100	84.400	250.0	0.00000	0.0000 254.00

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=GAMMA-CHLORDANE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	49.800	22.000	66.100	133.0	0.79600	17.2000	173.00
SM-O	0.000	0.000	0.000	.	0.00000	0.0000	0.00

----- Pollutant=HEPTACHLOR -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	32.000	12.400	37.100	116.0	0.44400	9.5700	96.50
SM-O	5.690	5.690	17.100	300.0	0.00000	0.0000	51.20

----- Pollutant=HEXACHLOROBENZENE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation of Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	4420.000	1950.000	5840.000	132.0	70.40000	1520.0000	15300.00
SM-O	0.000	0.000	0.000	.	0.00000	0.0000	0.00

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=HEXACHLOROBUTADIENE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	4420.000	1950.000	5840.000	132.0	70.40000	15300.00
SM-0	0.000	0.000	0.000	.	0.00000	0.00

----- Pollutant=LEAD -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	23.800	9.600	28.800	121.0	0.35200	76.60
SM-0	3.960	2.730	8.200	207.0	0.00000	24.80

----- Pollutant=LINDANE(GAMMA-BHC) -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	61.900	26.700	80.000	129.0	0.88000	211.00
SM-0	2.560	2.450	7.340	287.0	0.00000	22.10

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=MERCURY -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Standard Deviation of the Mean		Coefficient of Variation	Minimum	Median	Maximum
	Mean	Deviation				
SM-ML	0.138	0.044	0.132	95.4	0.00211	0.0760
SM-O	0.059	0.037	0.112	189.0	0.00000	0.0021
						0.35
						0.35

----- Pollutant=MOLYBDENUM -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Standard Deviation of the Mean		Coefficient of Variation	Minimum	Median	Maximum
	Mean	Deviation				
SM-ML	4.460	1.950	5.850	131.0	0.07040	1.5200
SM-O	0.328	0.328	0.984	300.0	0.00000	0.0000
						15.30
						2.95

----- Pollutant=N-NITROSODIMETHYLAMINE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Standard Deviation of the Mean		Coefficient of Variation	Minimum	Median	Maximum
	Mean	Deviation				
SM-ML	22100.000	9740.000	29200.000	132.0	352.00000	76600.00
SM-O	0.000	0.000	0.000	.	0.00000	0.0000
						0.0000
						0.00

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=NICKEL -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	18.900	7.800	23.400	124.0	0.56200	61.30
SM-O	4.470	2.870	8.620	193.0	0.00000	26.80

----- Pollutant=NITRATE+NITRITE (AS N) -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	68.600	17.200	51.700	75.4	6.34000	153.00
SM-O	36.400	11.600	34.900	95.9	0.00000	91.20

----- Pollutant=PCB(TOTAL) -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	771.000	341.000	1020.000	133.0	12.30000	2680.00
SM-O	0.000	0.000	0.000	0.00000	0.00000	0.000

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=SELENIUM -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	4.370	1.240	3.720	85.2	0.03520	2.7400	10.20
SM-O	0.487	0.335	1.000	206.0	0.00000	0.0000	2.74

----- Pollutant=TOTAL KJELDAHL NITROGEN -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	23600.000	8350.000	25100.000	106.0	218.00000	13000.0000	84200.00
SM-O	23600.000	8350.000	25100.000	106.0	218.00000	13000.0000	84200.00

----- Pollutant=TOTAL PHOSPHOROUS -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Standard Deviation	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	4580.000	1050.000	3150.000	68.7	176.00000	3500.0000	10700.00
SM-O	4580.000	1050.000	3150.000	68.7	176.00000	3500.0000	10700.00

Dry Weight Concentrations of Pollutants in Septage:
Summary Statistics from Substitution Methods

----- Pollutant=TOXAPHENE -- Sample Size=9 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	3240.000	1600.000	4800.000	148.0	80.10000	1390.0000
SM-O	0.000	0.000	0.000	.	0.00000	15500.00
					0.0000	0.00

----- Pollutant=TRICHLOROETHENE -- Sample Size=7 -- Units=UG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	1540.000	519.000	1370.000	89.1	70.40000	1080.0000
SM-O	0.000	0.000	0.000	.	0.00000	4330.00
					0.0000	0.00

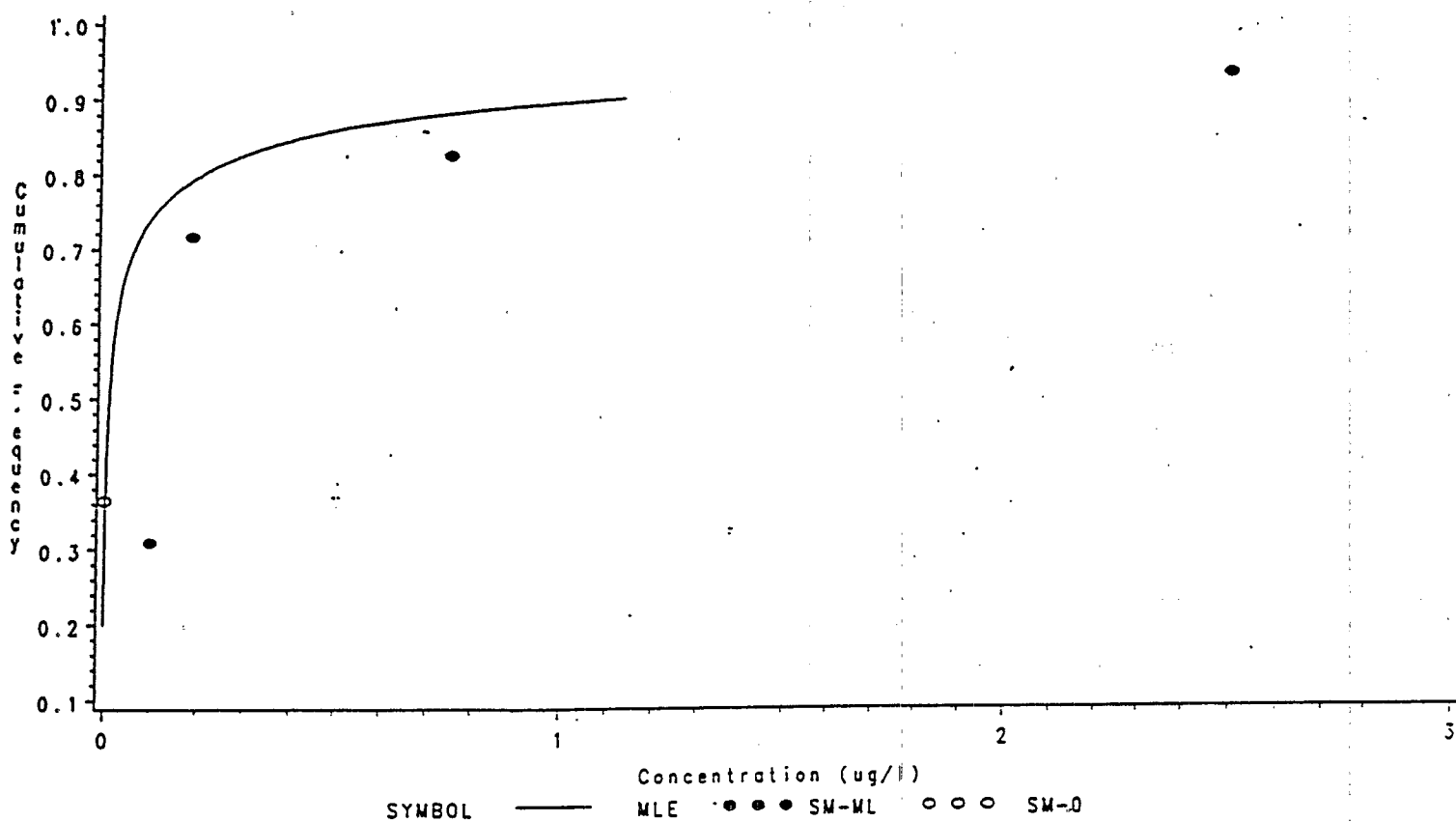
----- Pollutant=ZINC -- Sample Size=9 -- Units=MG/KG -----

Substitution Method	Mean	Standard Deviation of the Mean	Coefficient of Variation	Minimum	Median	Maximum
SM-ML	570.000	146.000	439.000	77.1	43.70000	1290.00
SM-O	570.000	146.000	439.000	77.1	43.70000	1290.00

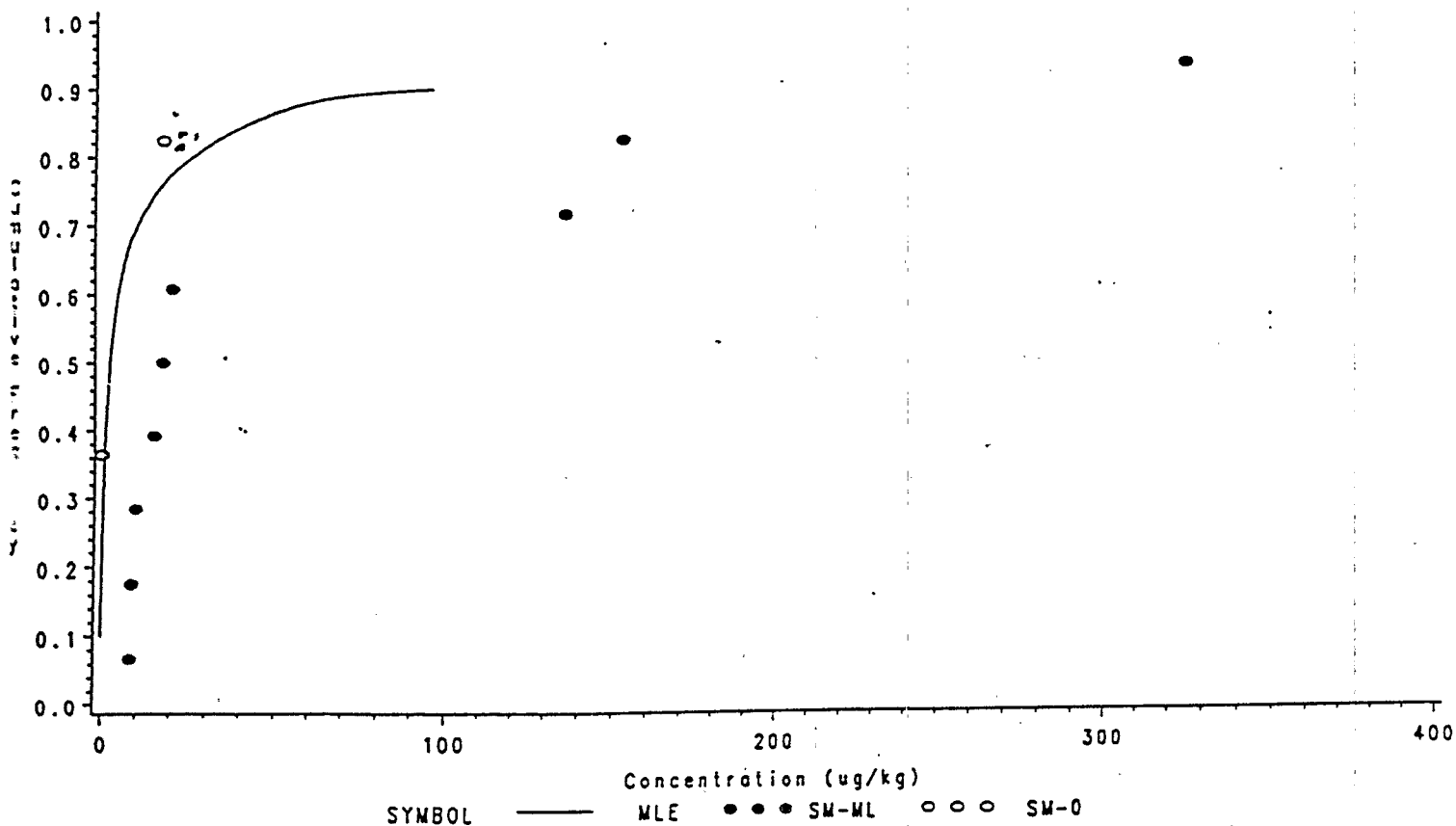
Appendix B

Graphics

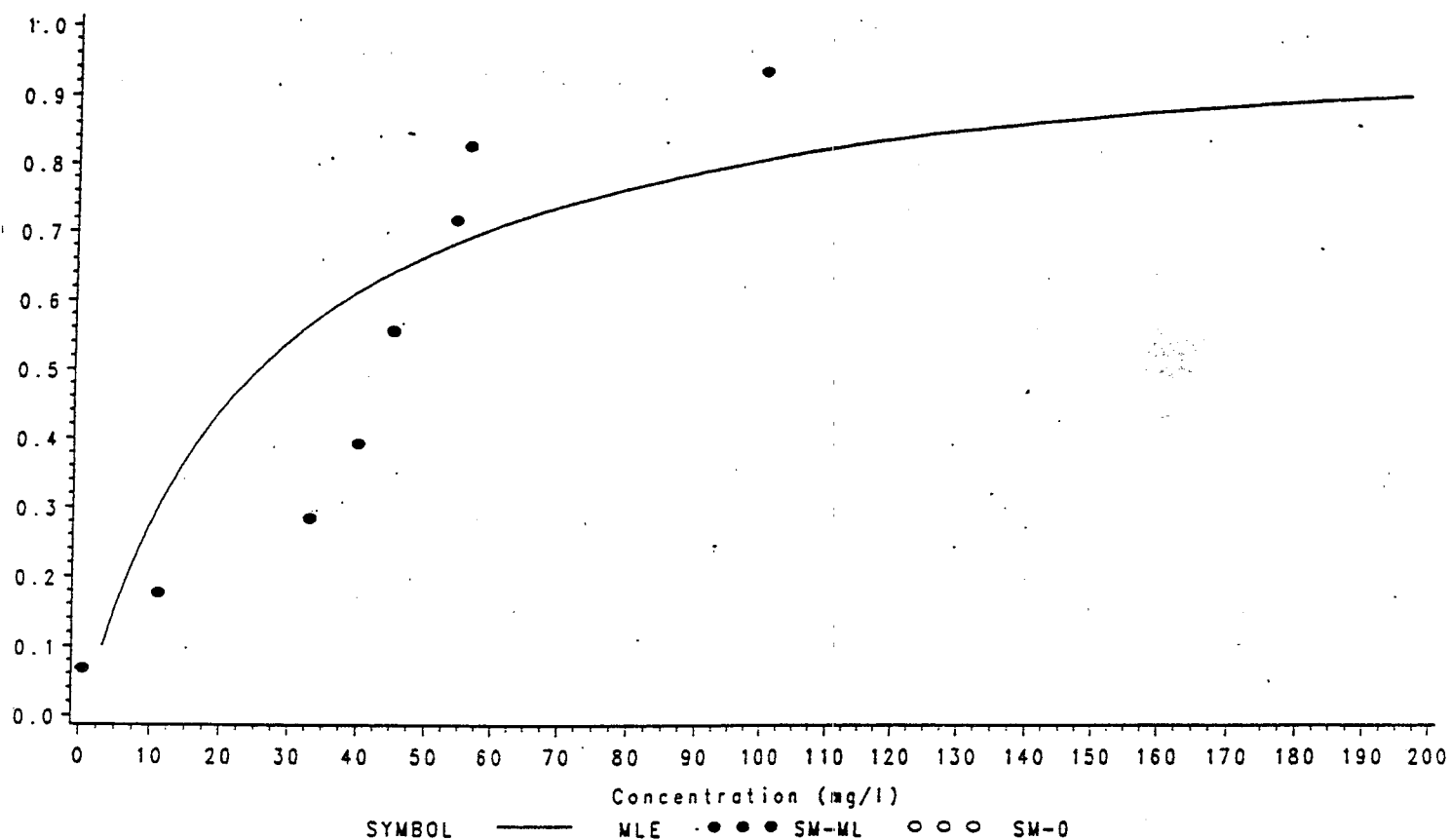
Cumulative Frequency for Total Aldrin/Dieldrin (ug/l)



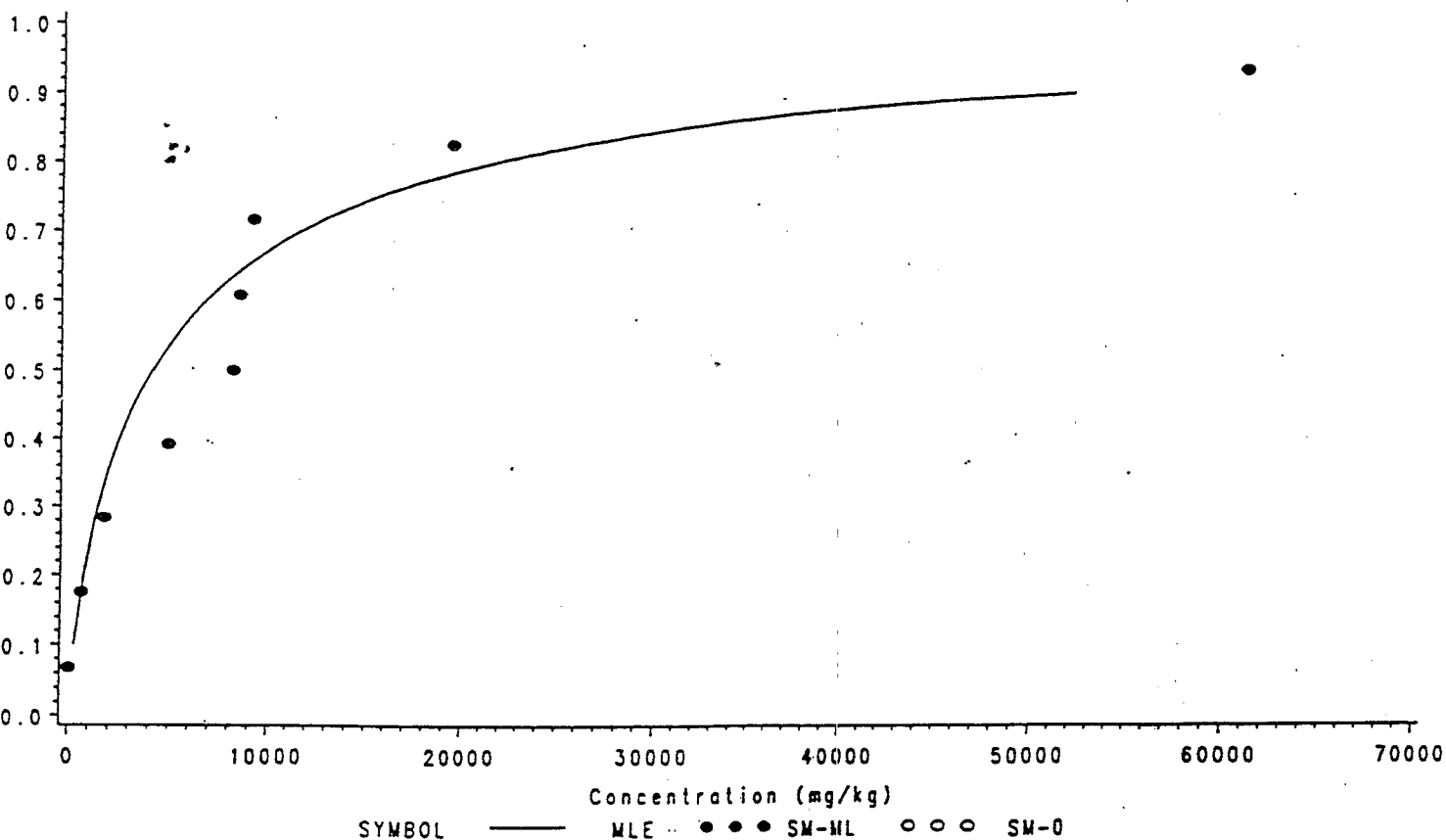
Cumulative Frequency for Total Aldrin/Dieldrin (ug/kg)



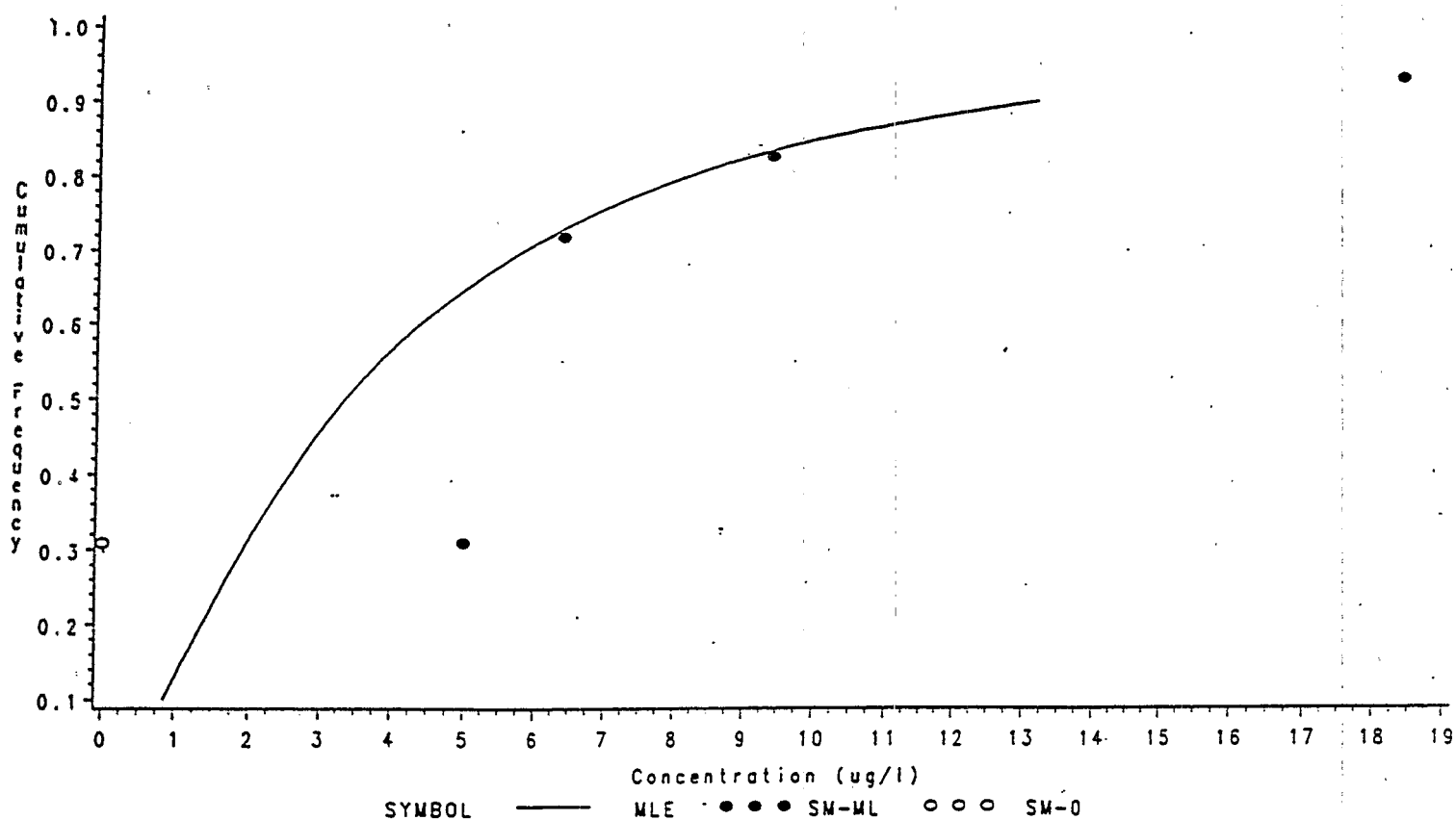
Cumulative Frequency for Ammonia (AS N) (mg/l)



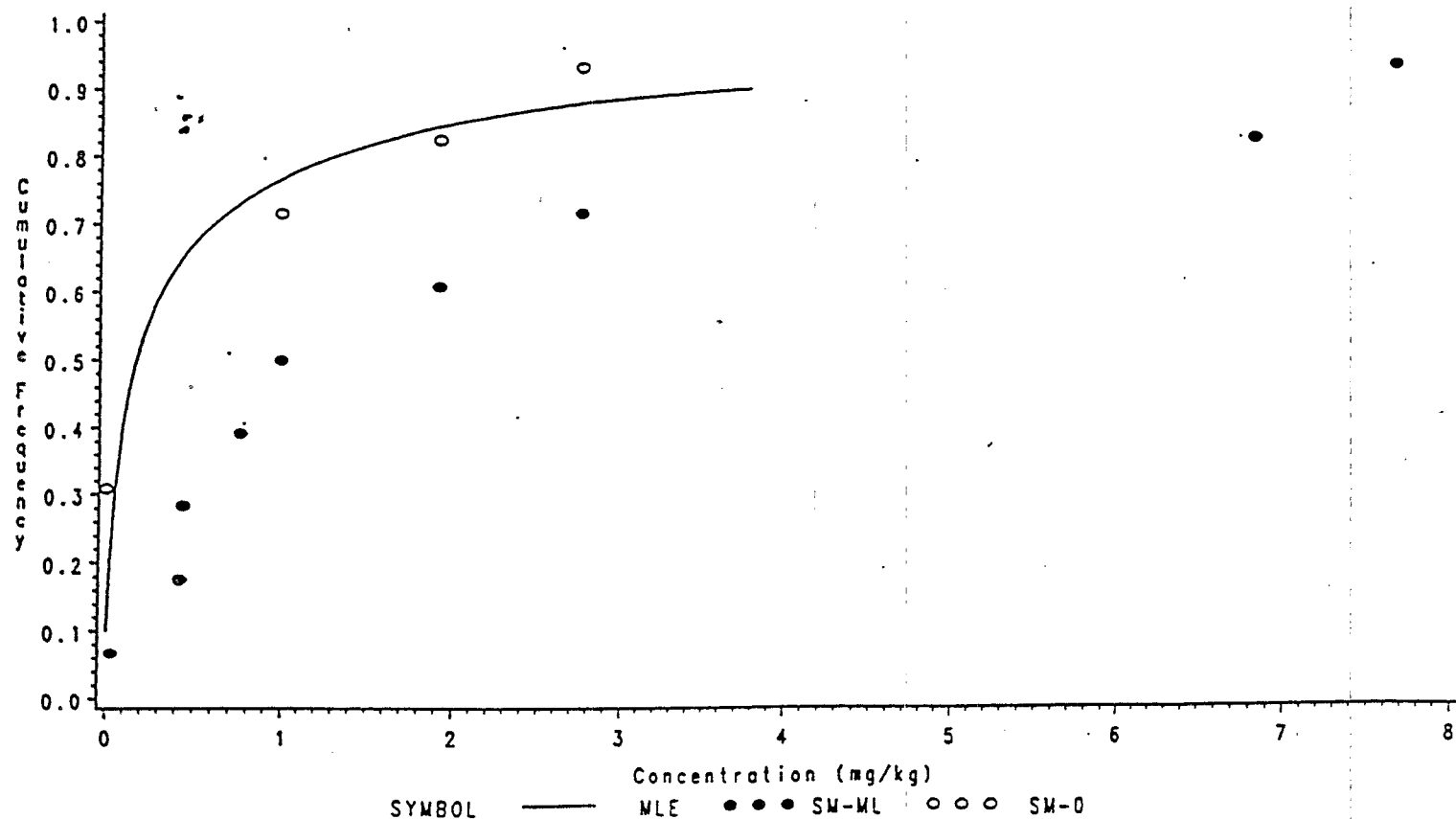
Cumulative Frequency for Ammonia (AS N) (mg/kg)



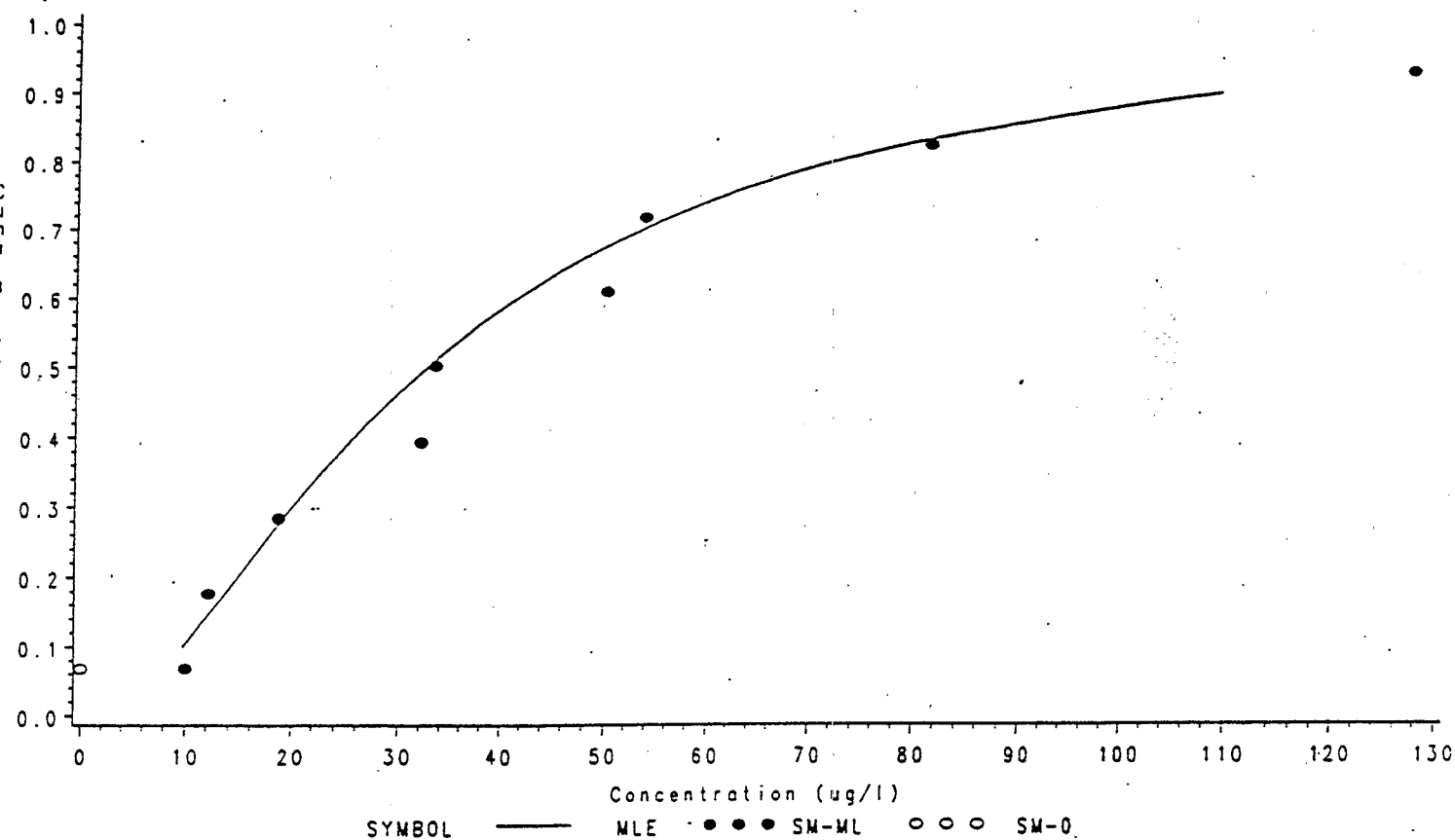
Cumulative Frequency for Cadmium (ug/l)



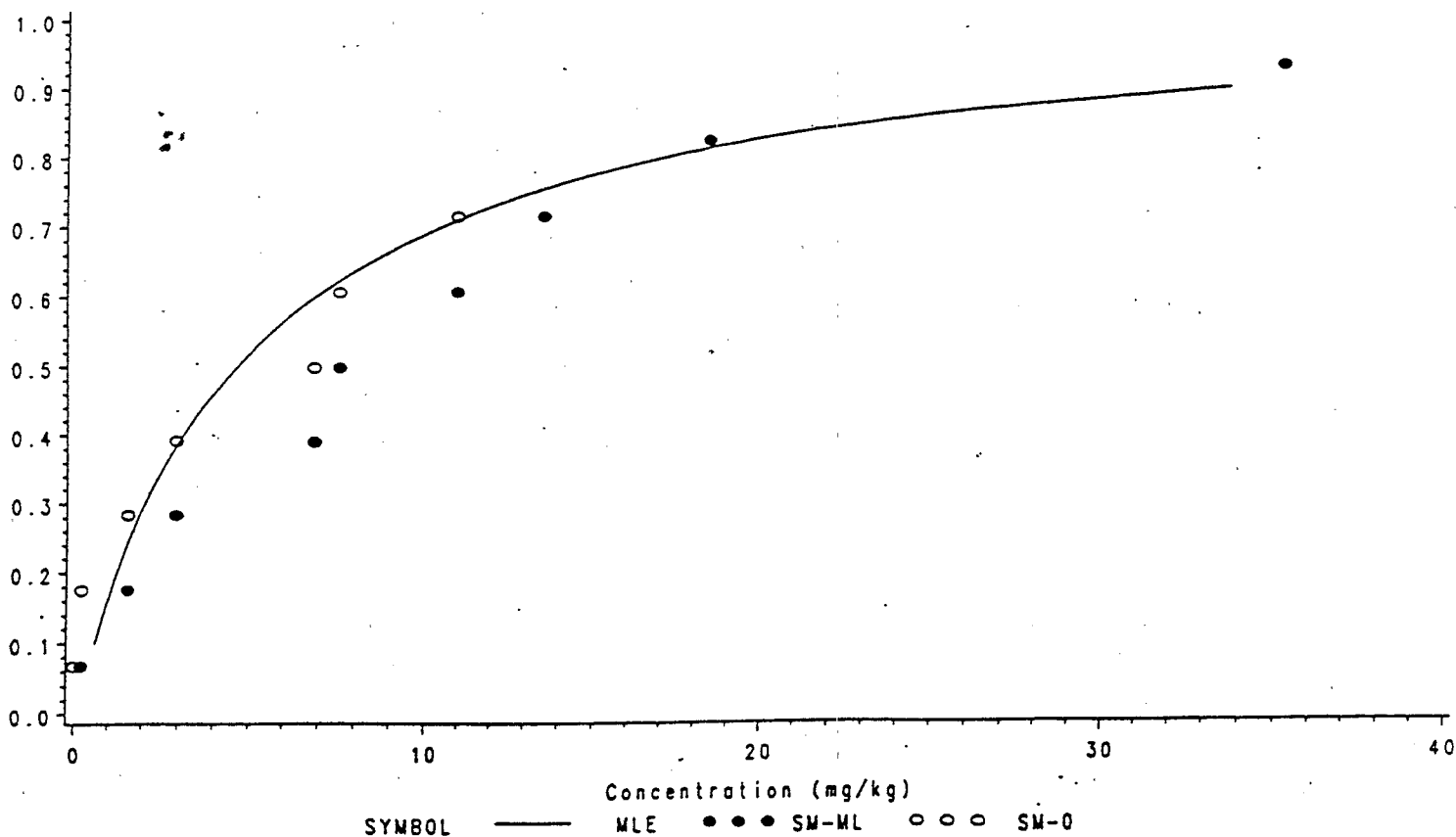
Cumulative Frequency for Cadmium (mg/kg)



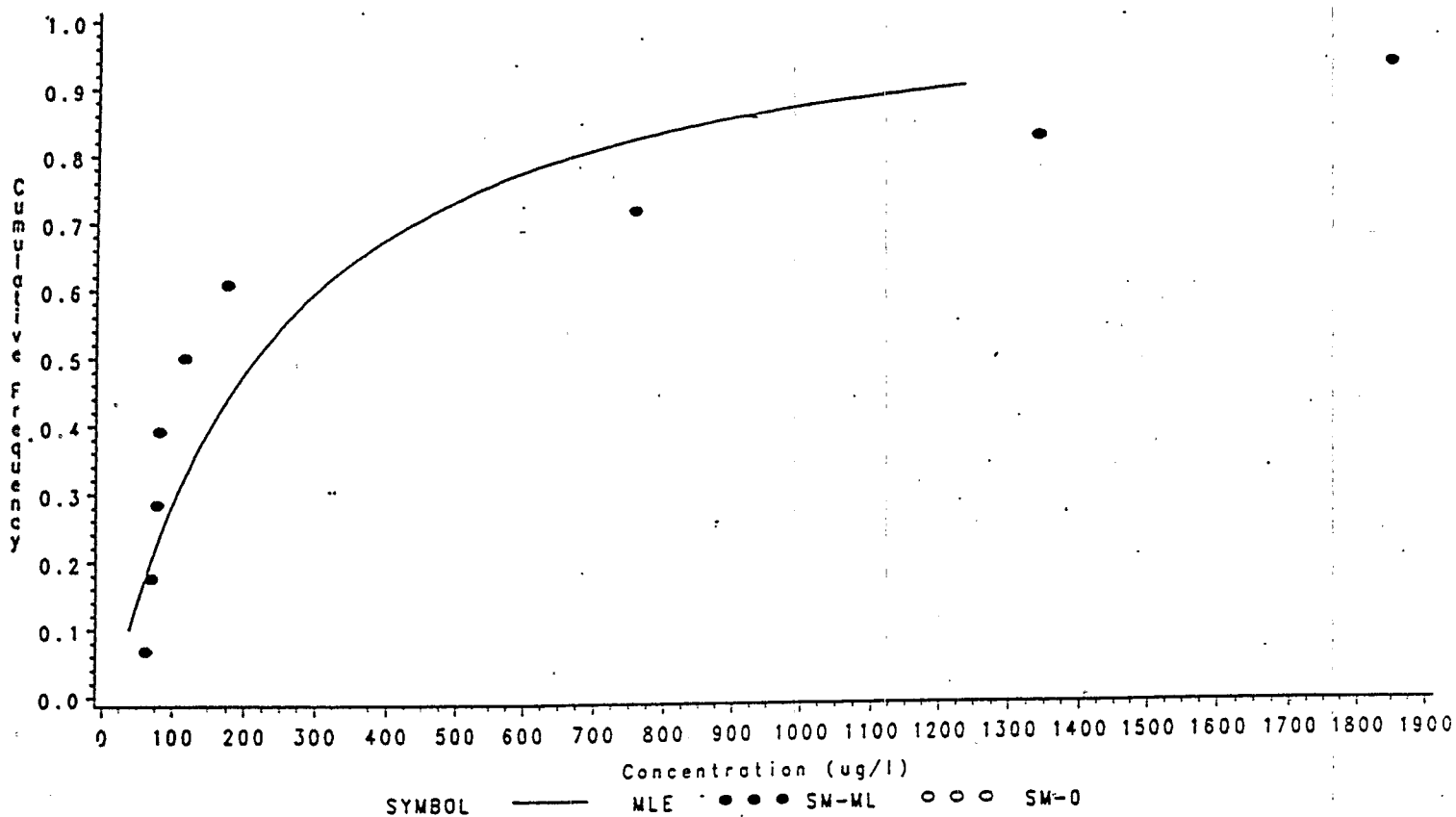
Cumulative Frequency for Chromium (ug/l)



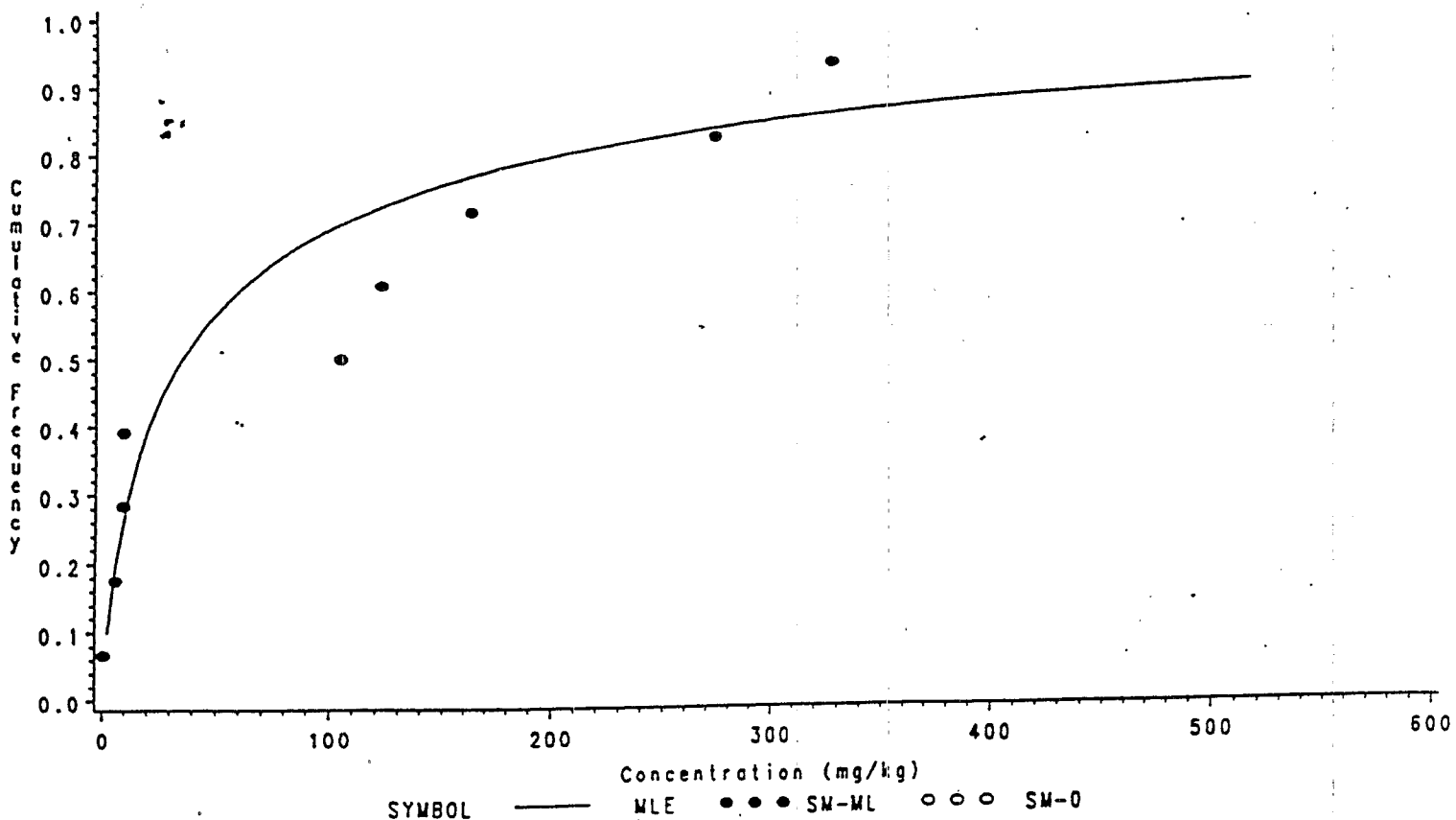
Cumulative Frequency for Chromium (mg/kg)



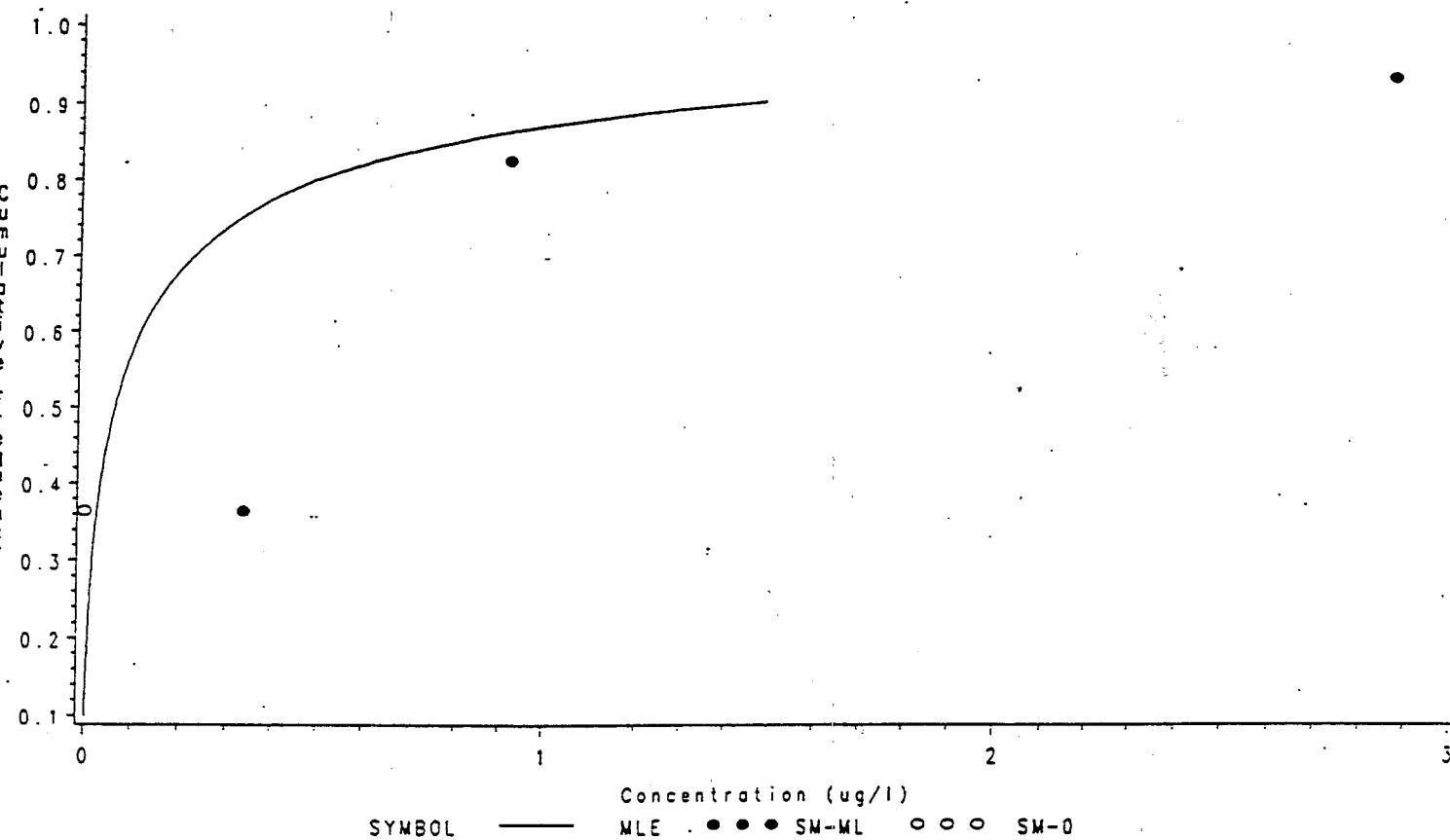
Cumulative Frequency for Copper (ug/l)



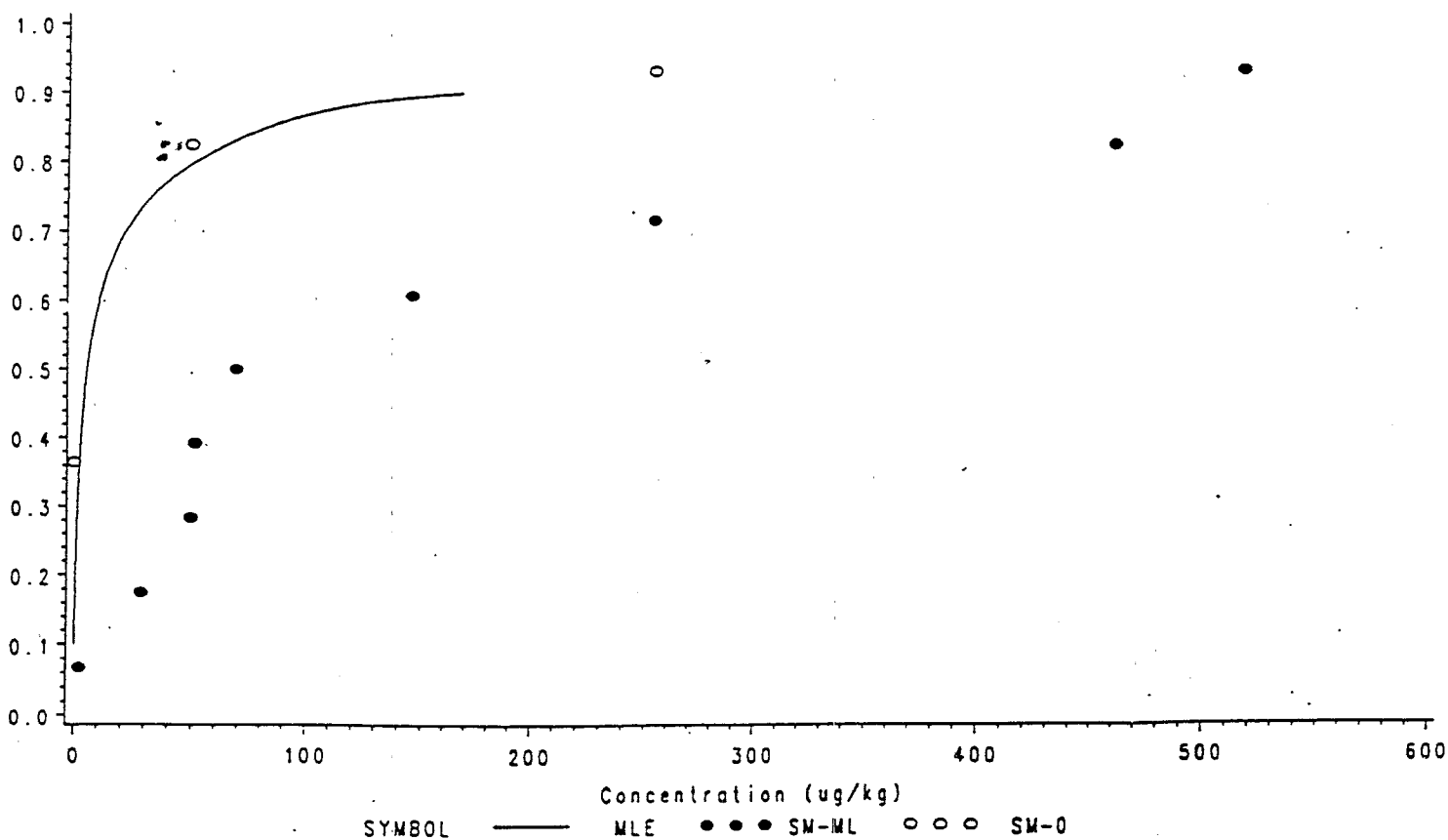
Cumulative Frequency for Copper (mg/kg)



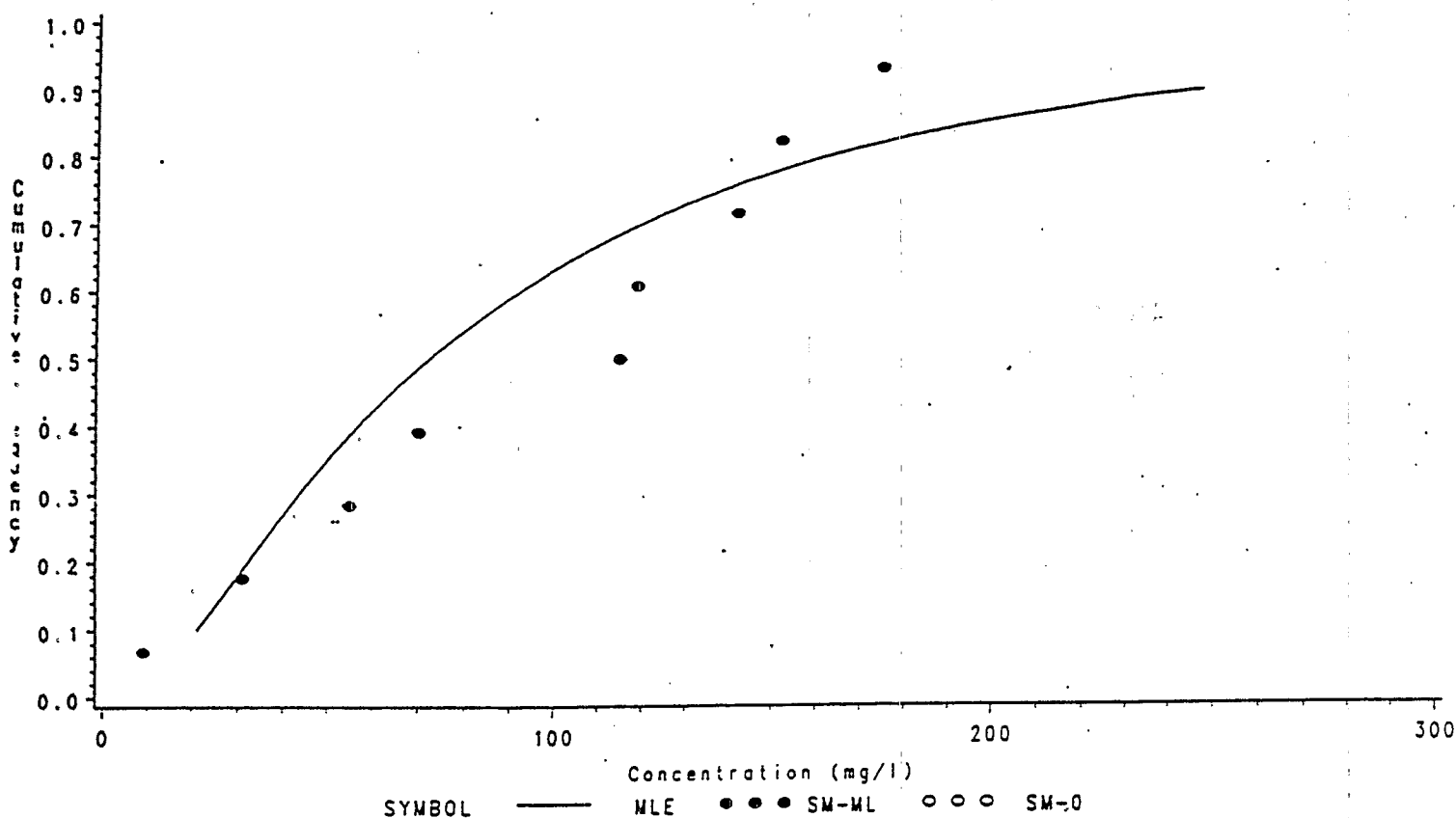
Cumulative Frequency for Total DDT, DDE, and DDD (ug/l)



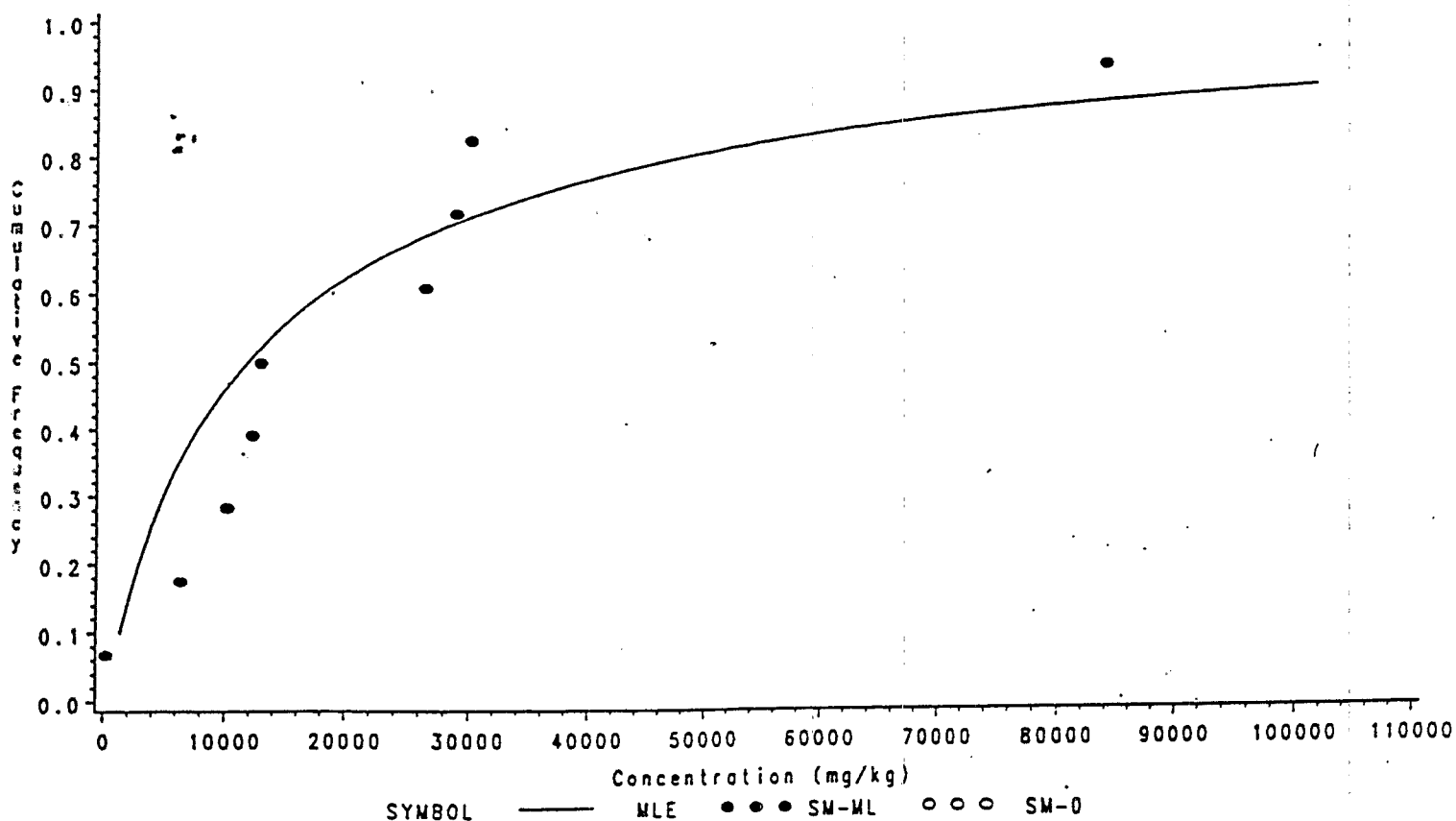
Cumulative Frequency for Total DDT, DDE, and DDD (ug/kg)



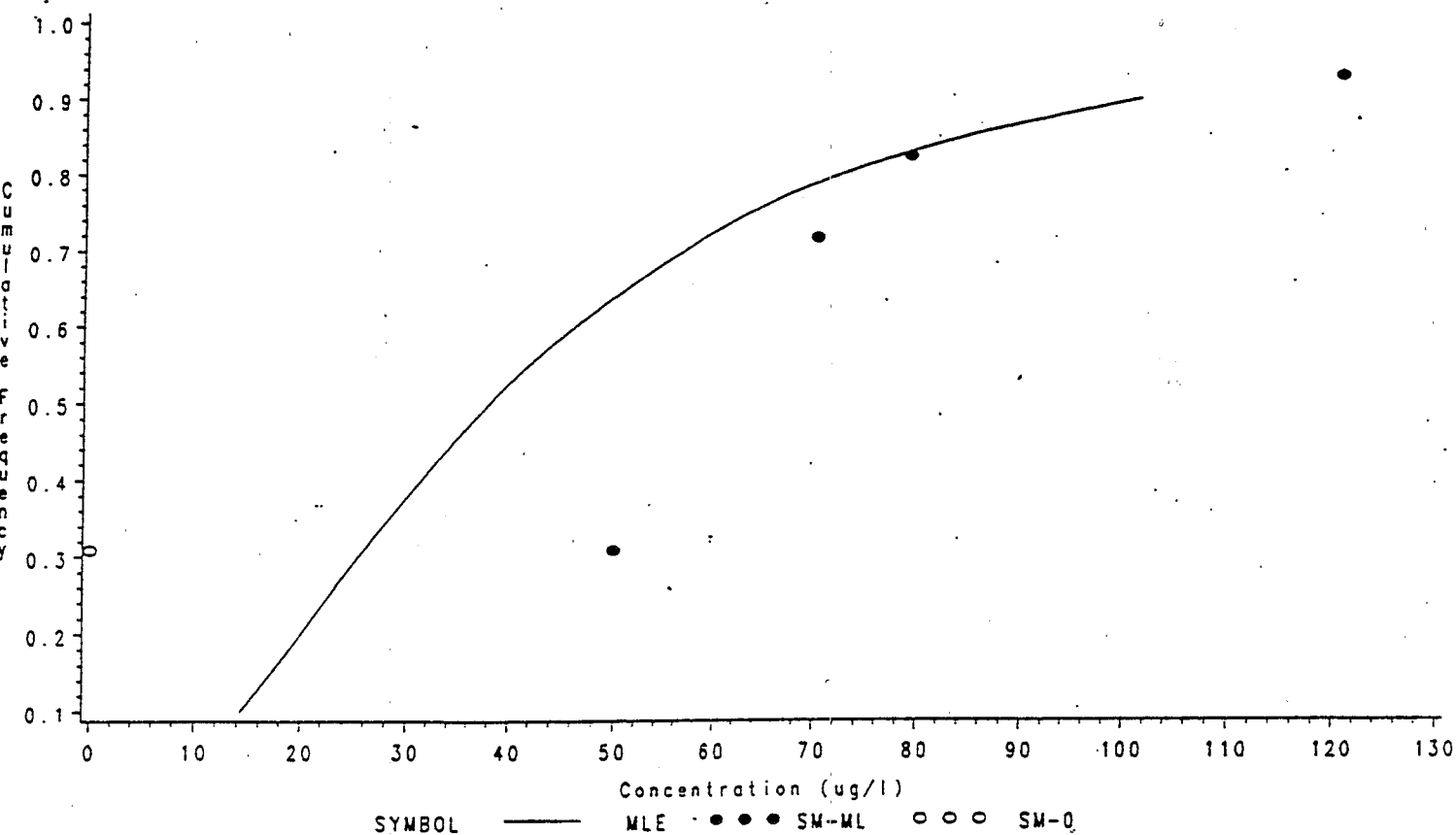
Cumulative Frequency for Total Kjeldahl Nitrogen (mg/l)



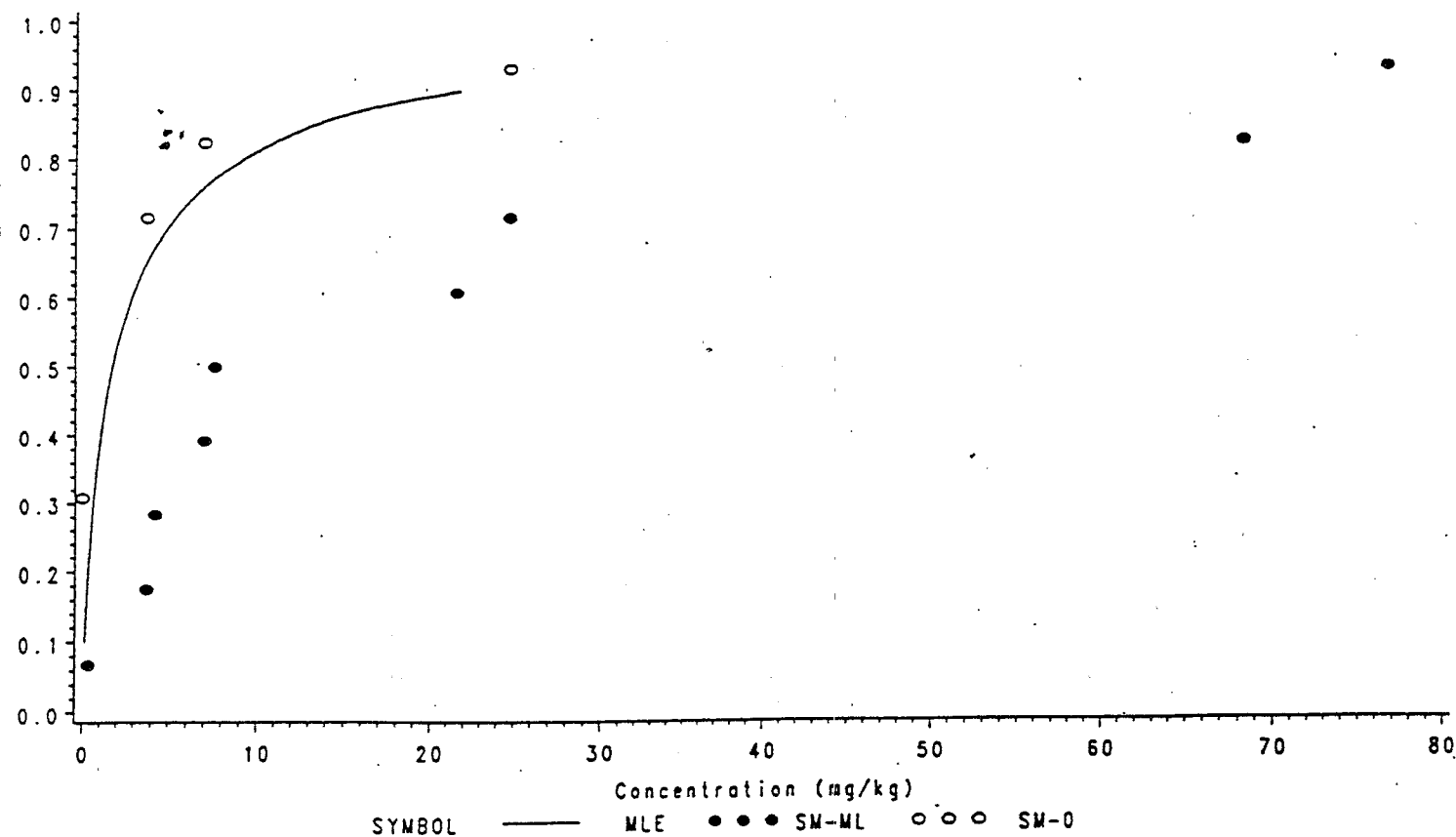
Cumulative Frequency for Total Kjeldahl Nitrogen (mg/kg)



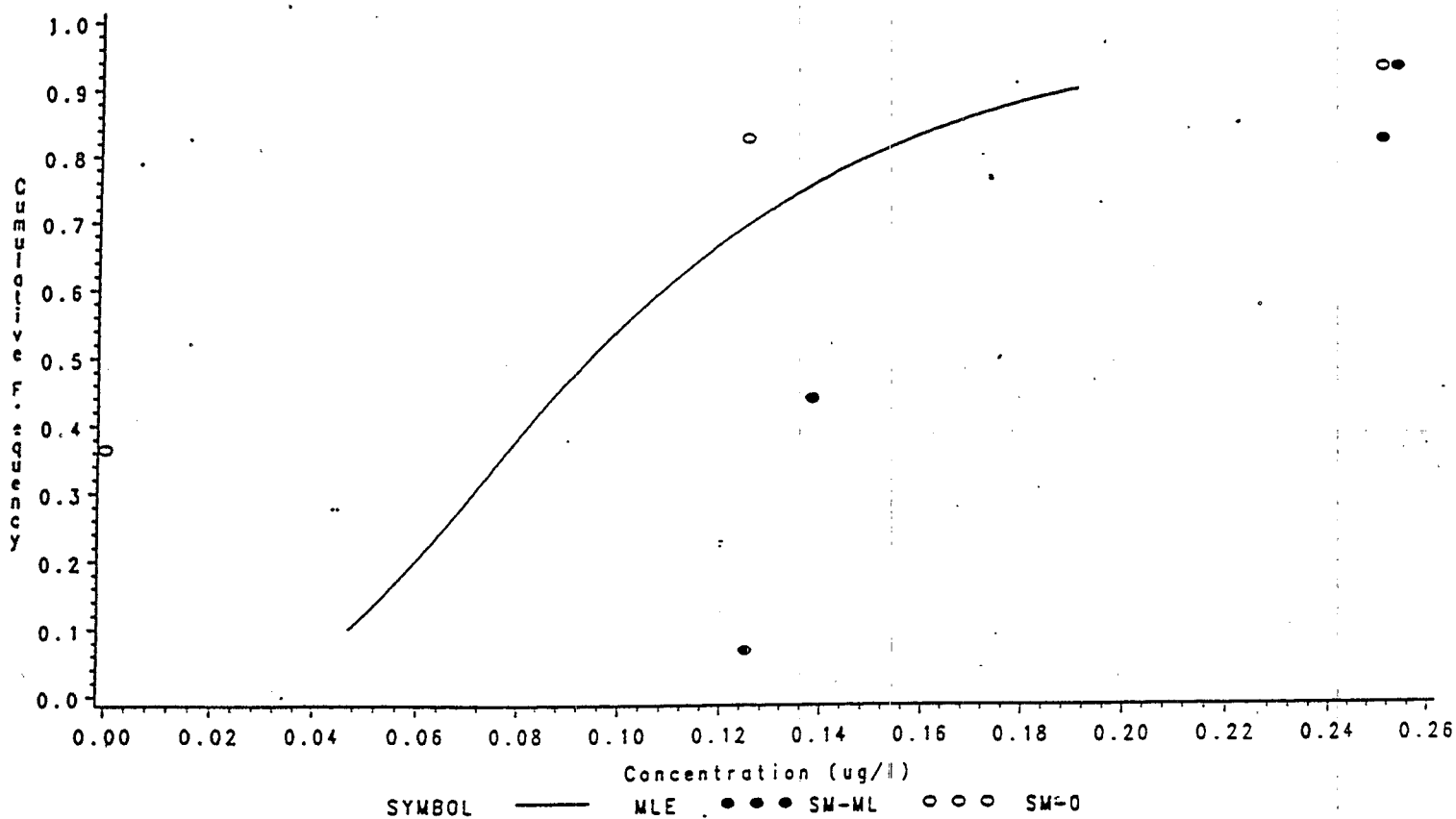
Cumulative Frequency for Lead (ug/l)



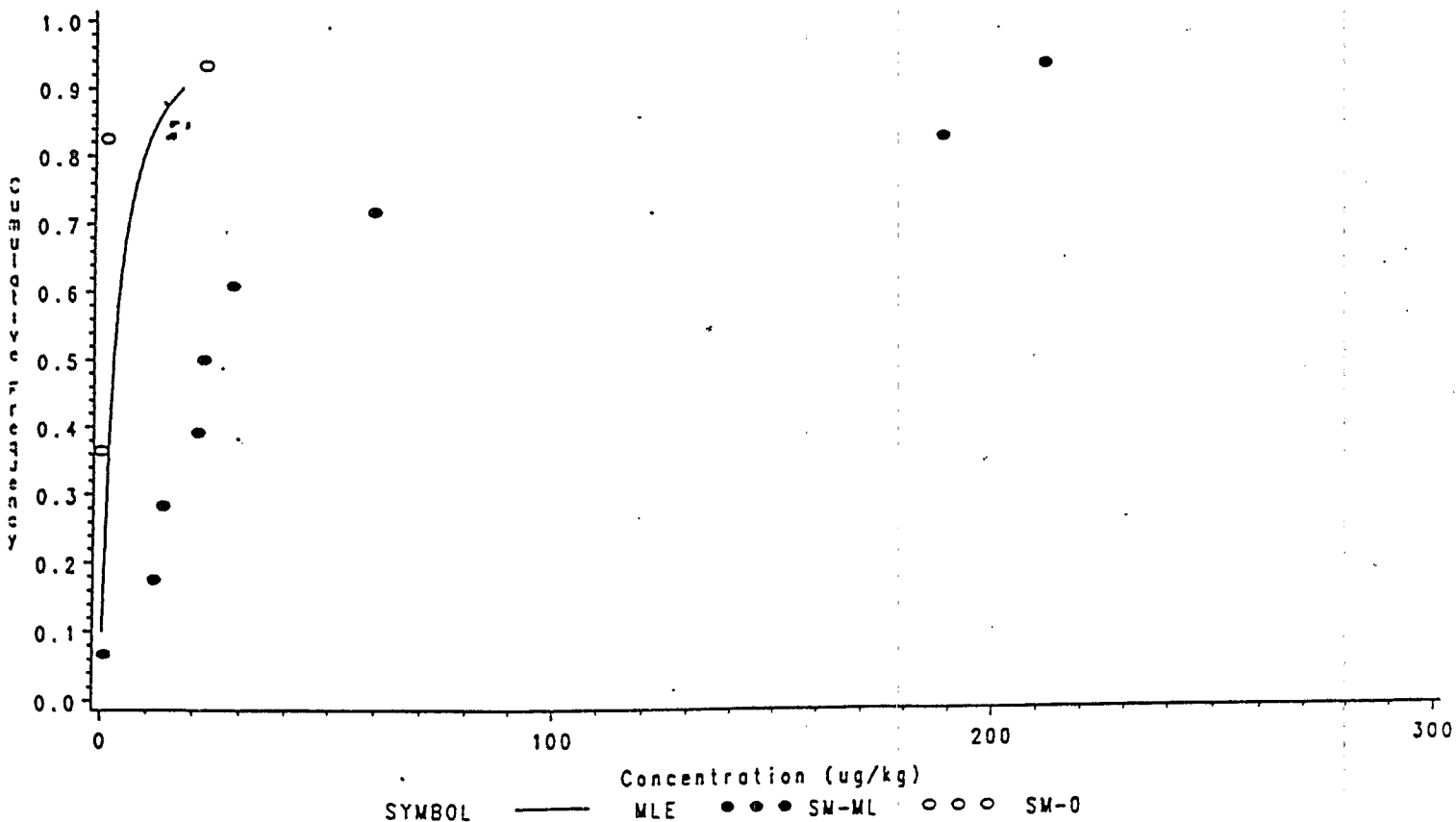
Cumulative Frequency for Lead (mg/kg)



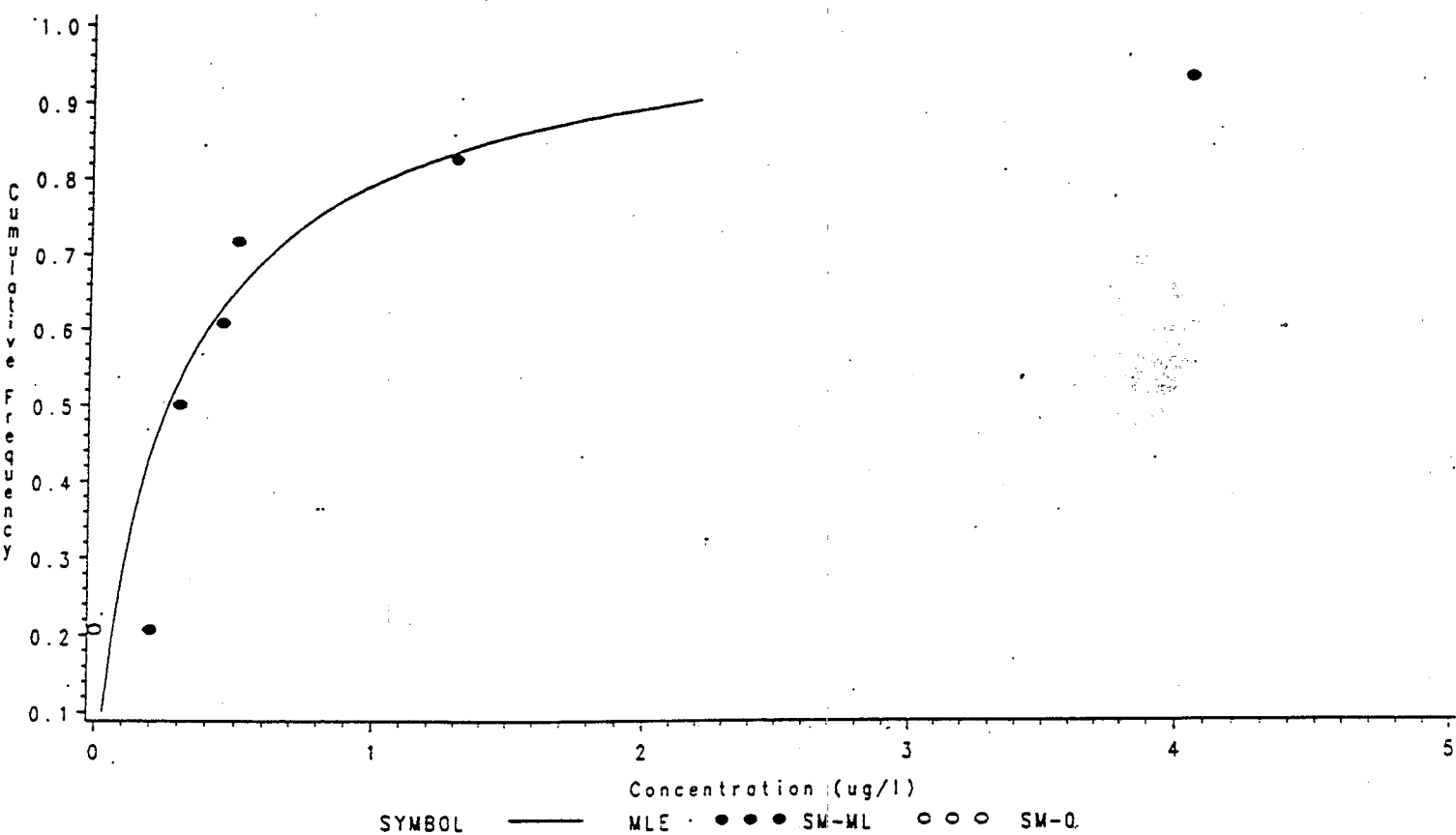
Cumulative Frequency for Lindane (Gamma-BHC) (ug/l)



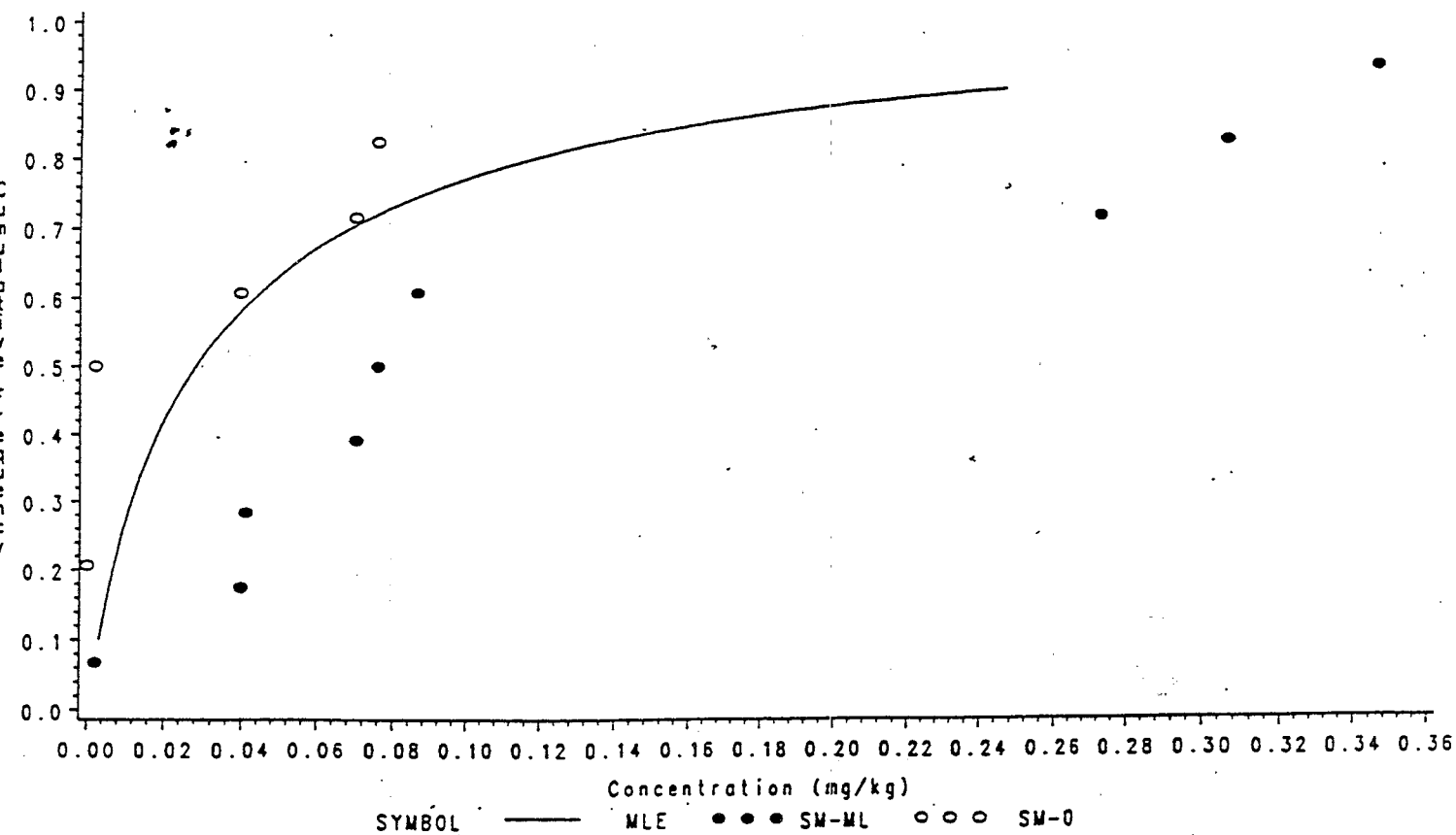
Cumulative Frequency for Lindane (Gamma-BHC) (ug/kg)



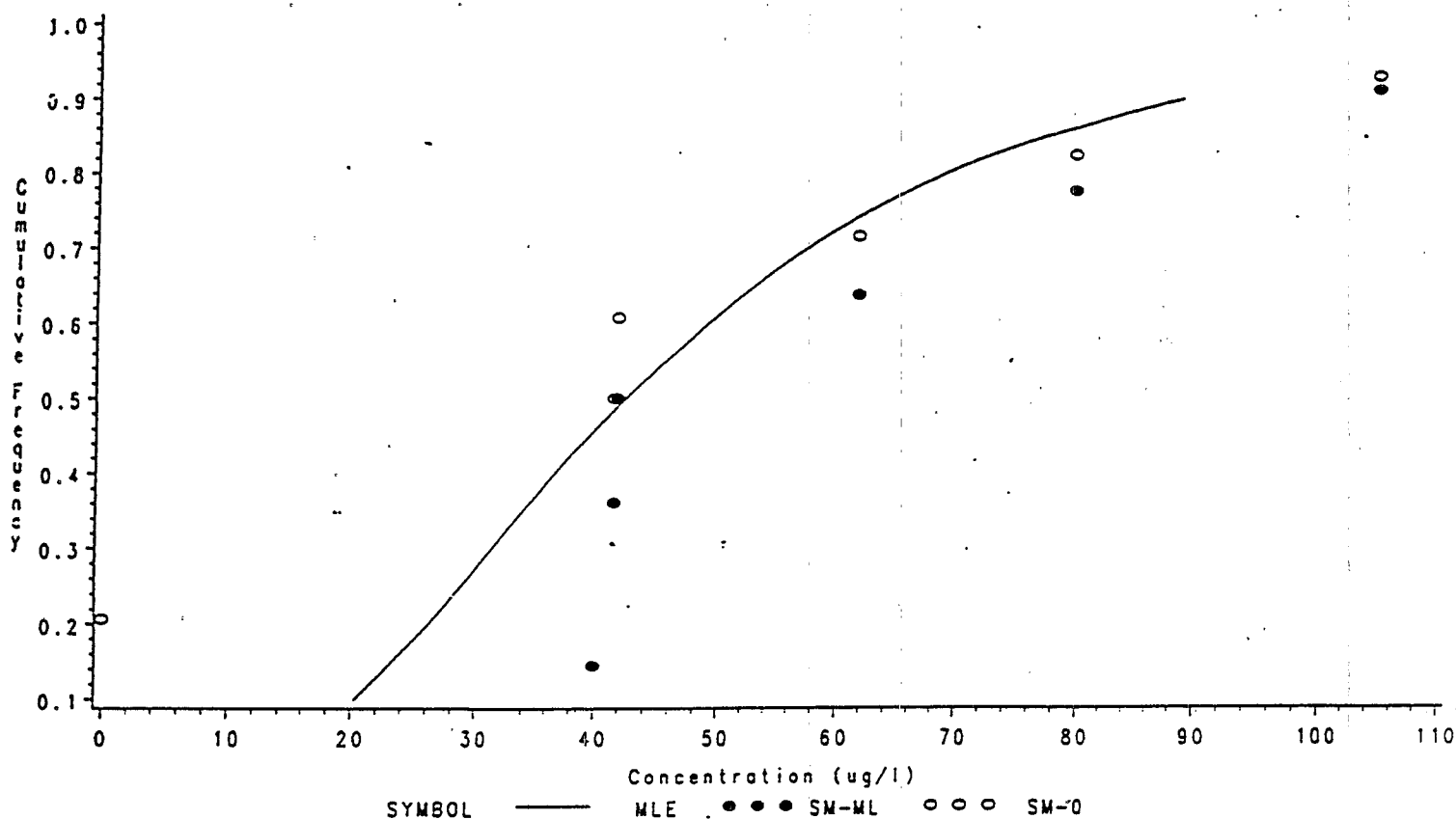
Cumulative Frequency for Mercury (ug/l)



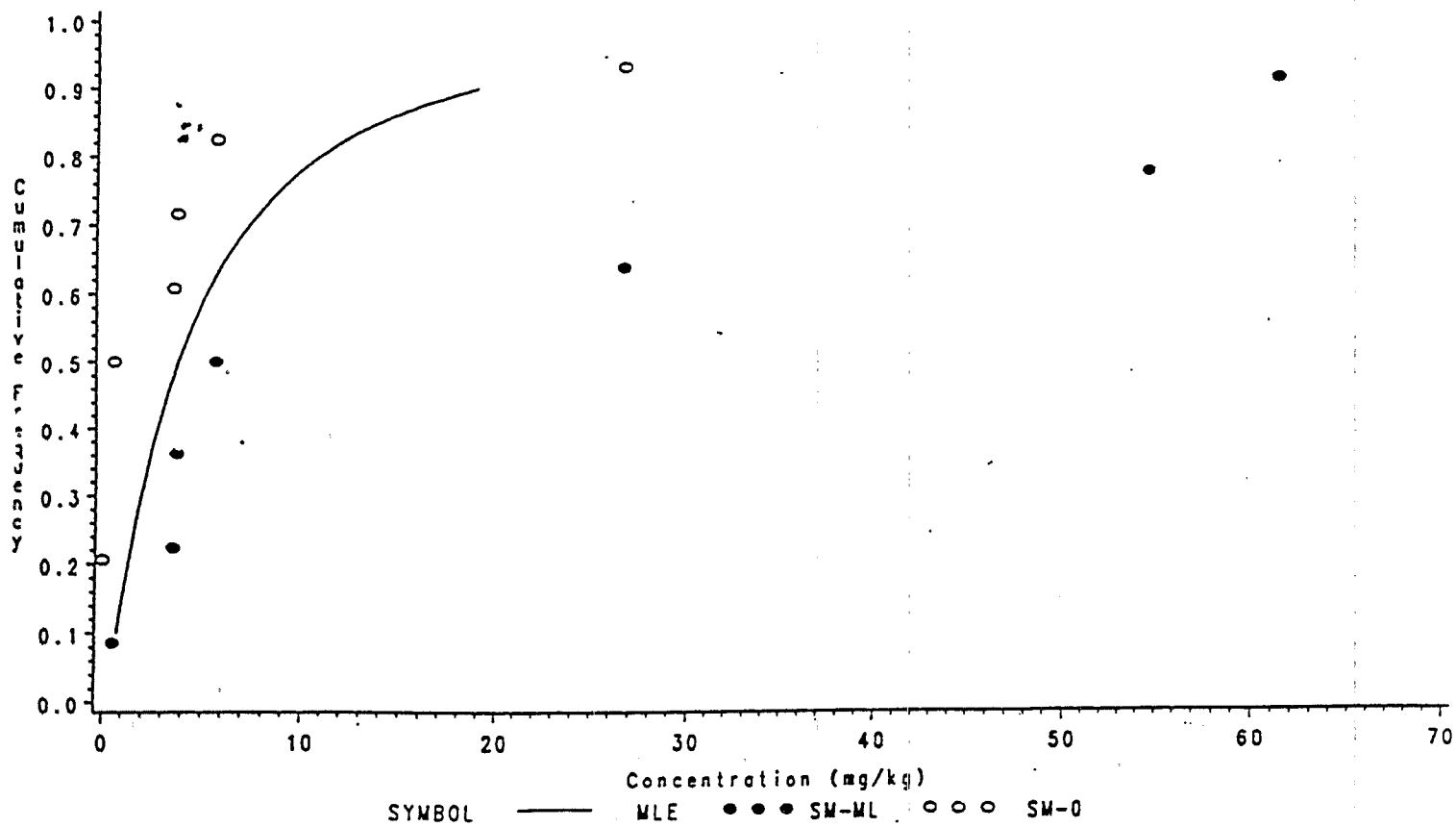
Cumulative Frequency for Mercury (mg/kg)



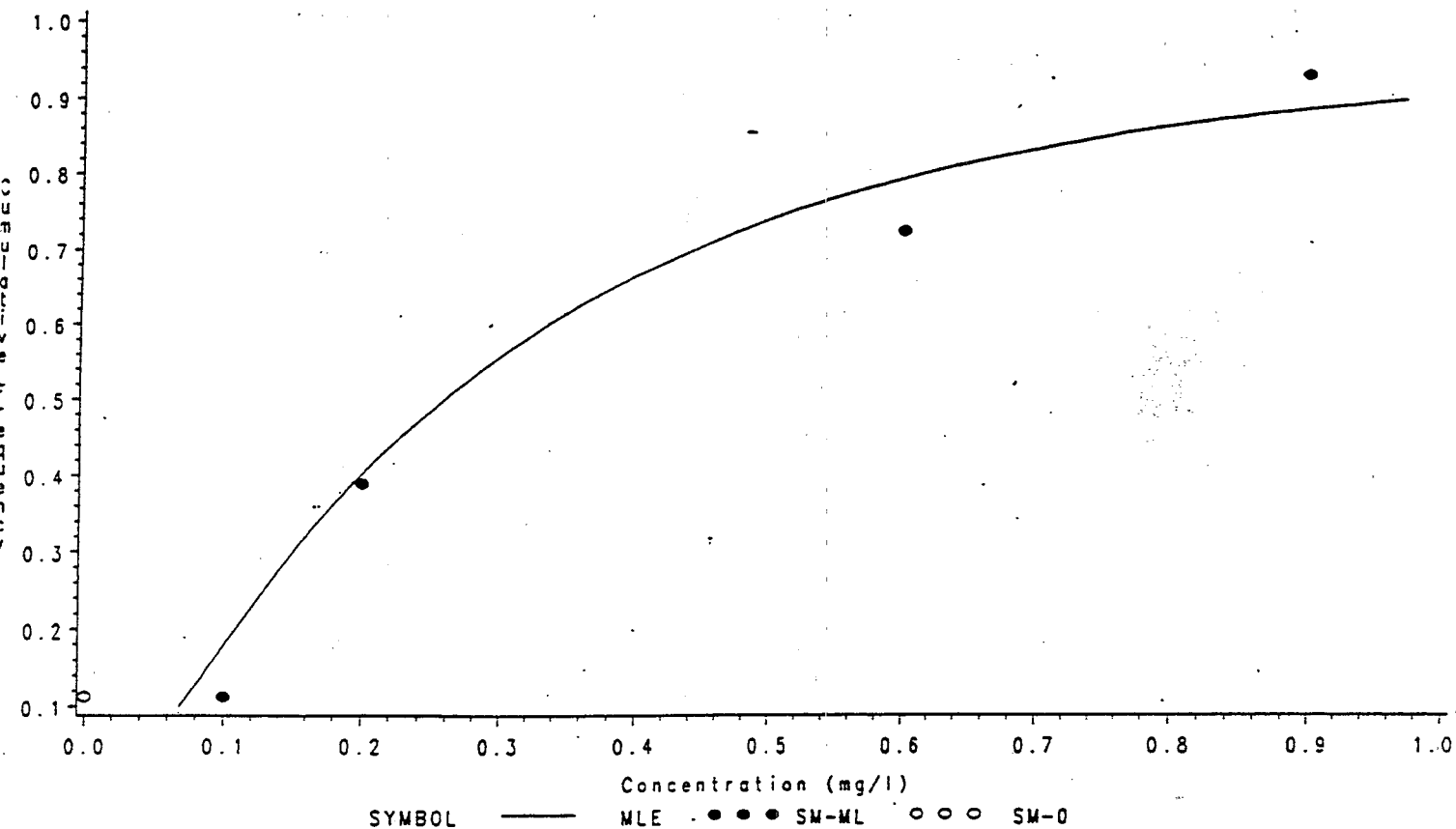
Cumulative Frequency for Nickel (ug/l)



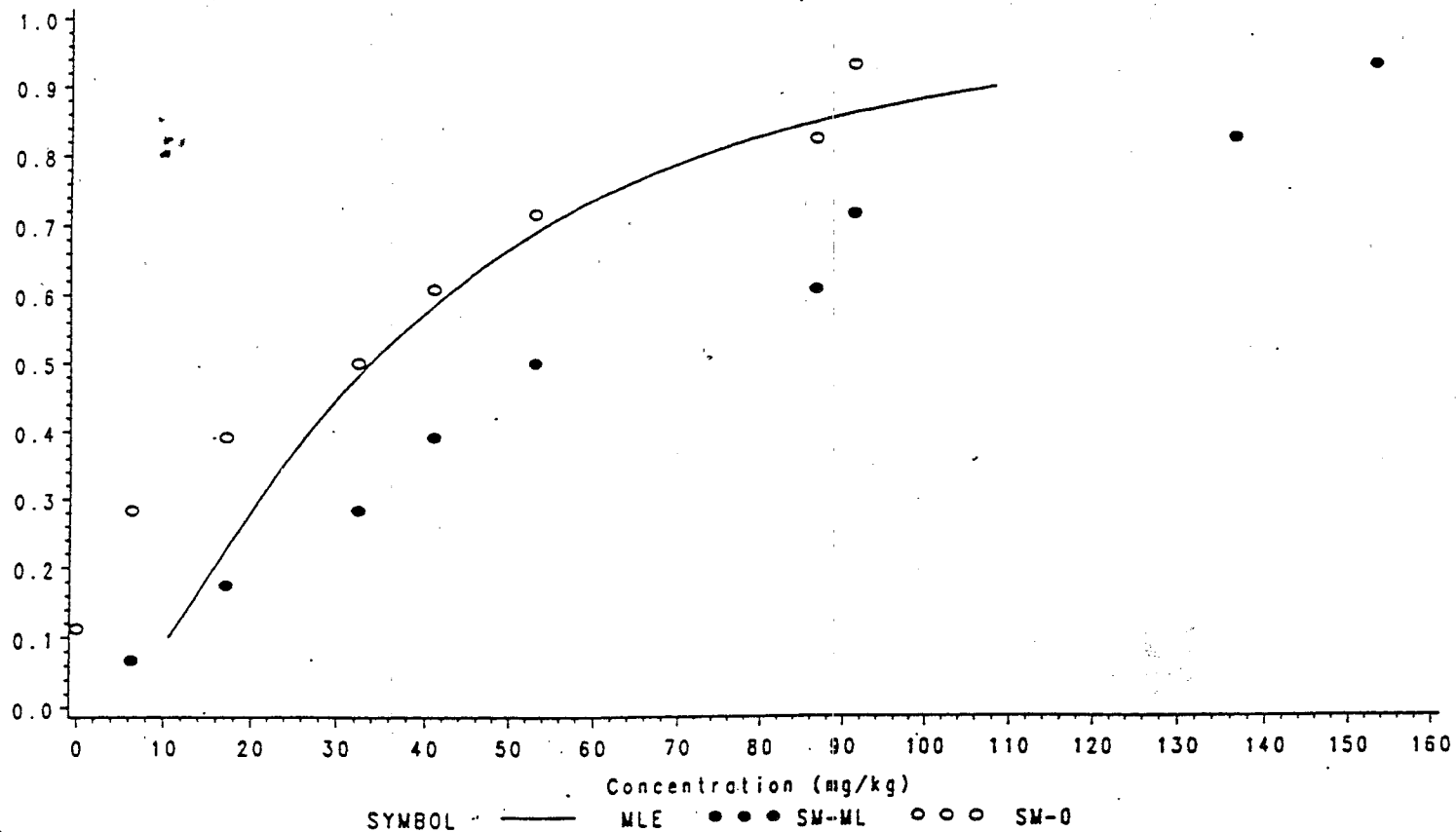
Cumulative Frequency for Nickel (mg/kg)



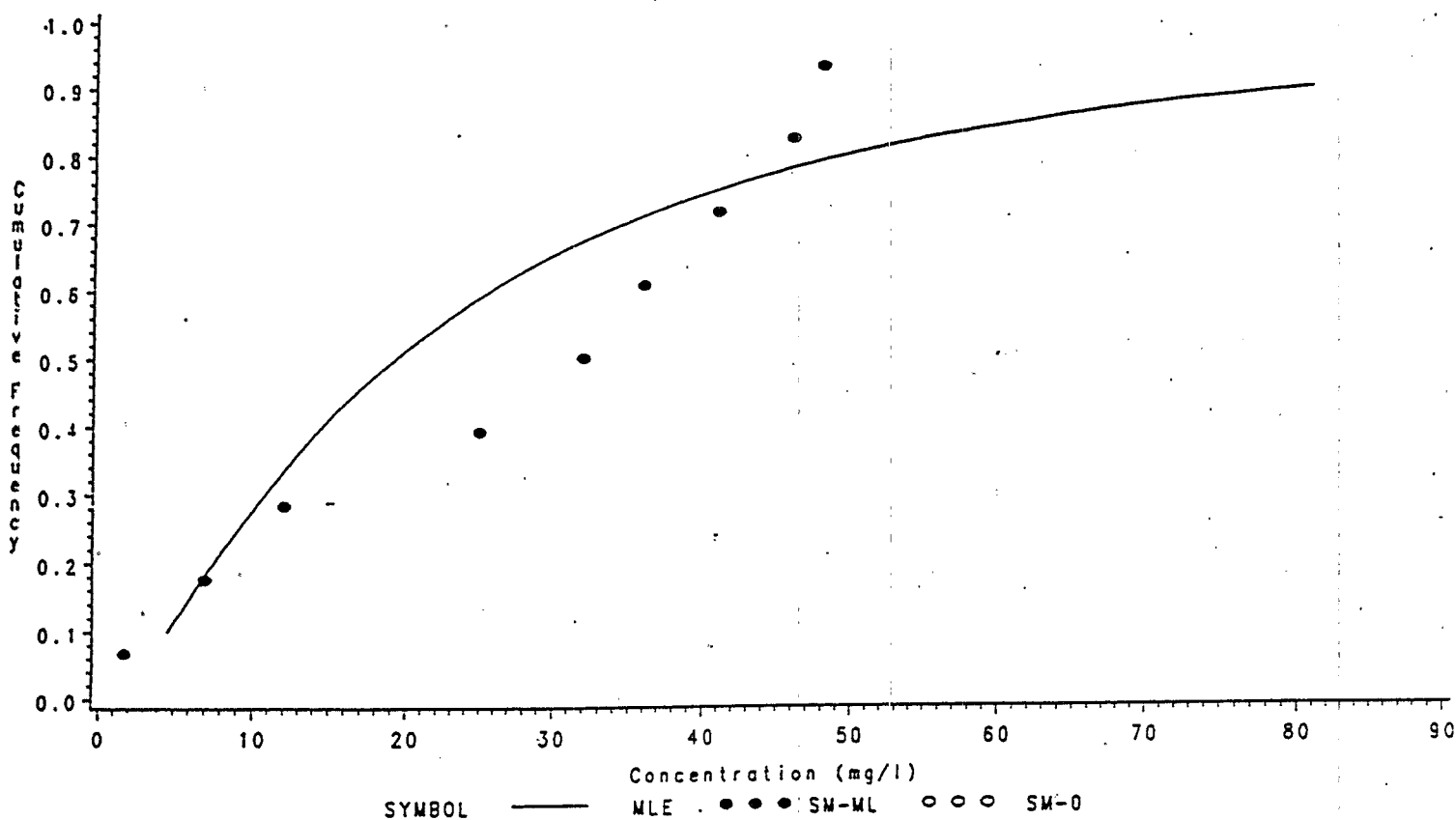
Cumulative Frequency for Nitrate + Nitrite (mg/l)



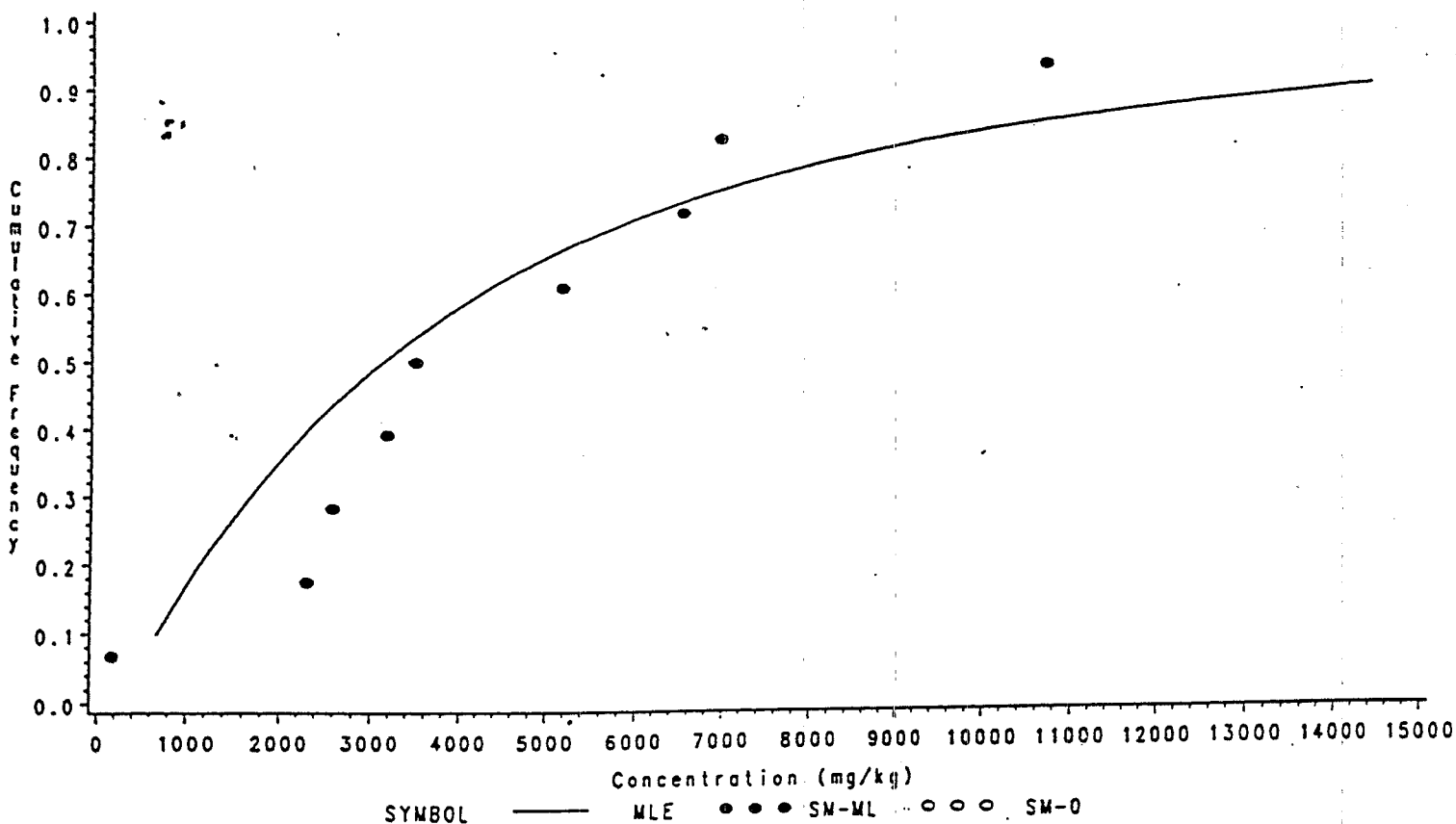
Cumulative Frequency for Nitrate + Nitrite (mg/kg)



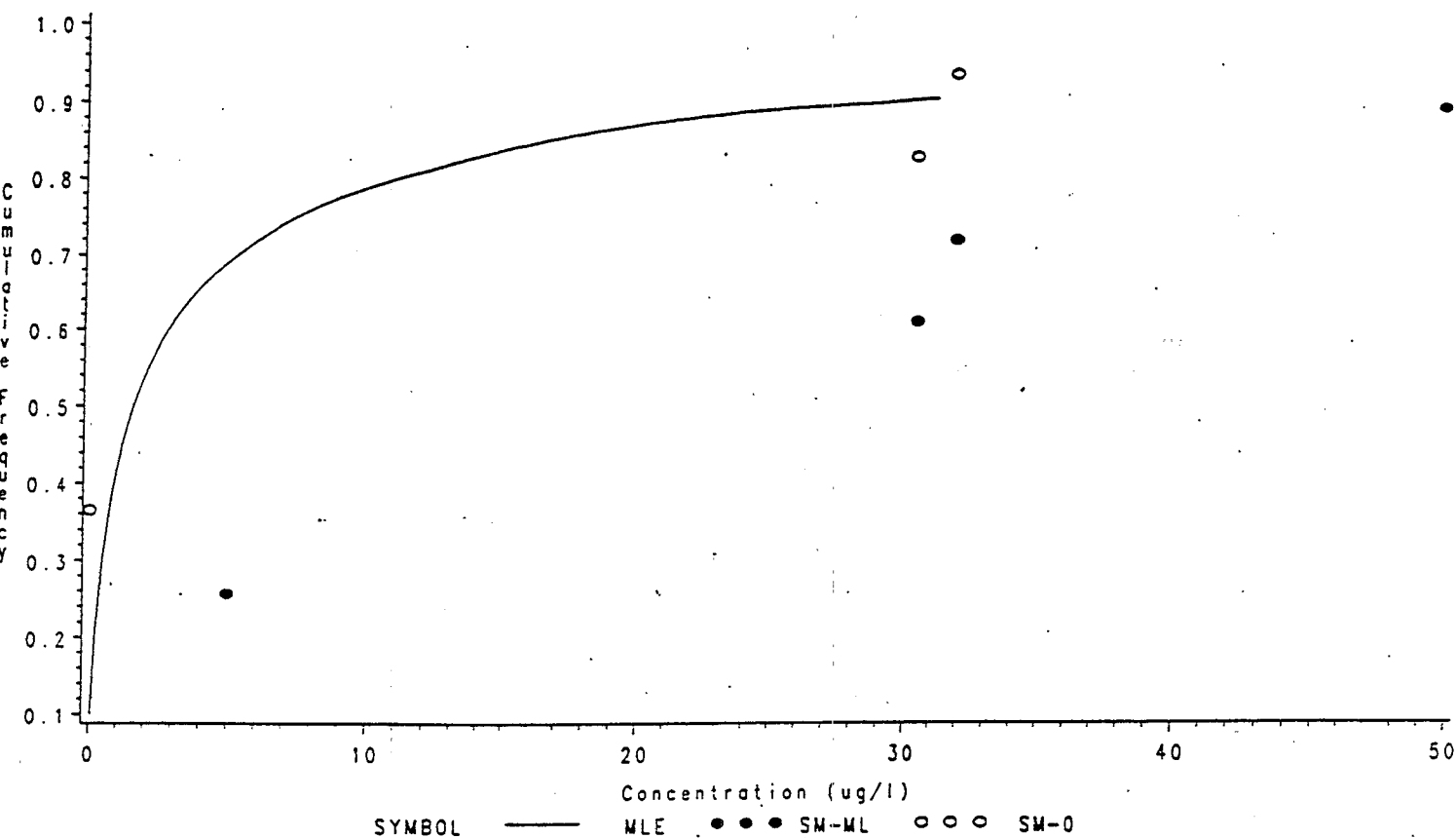
Cumulative Frequency for Total Phosphorous (mg/l)



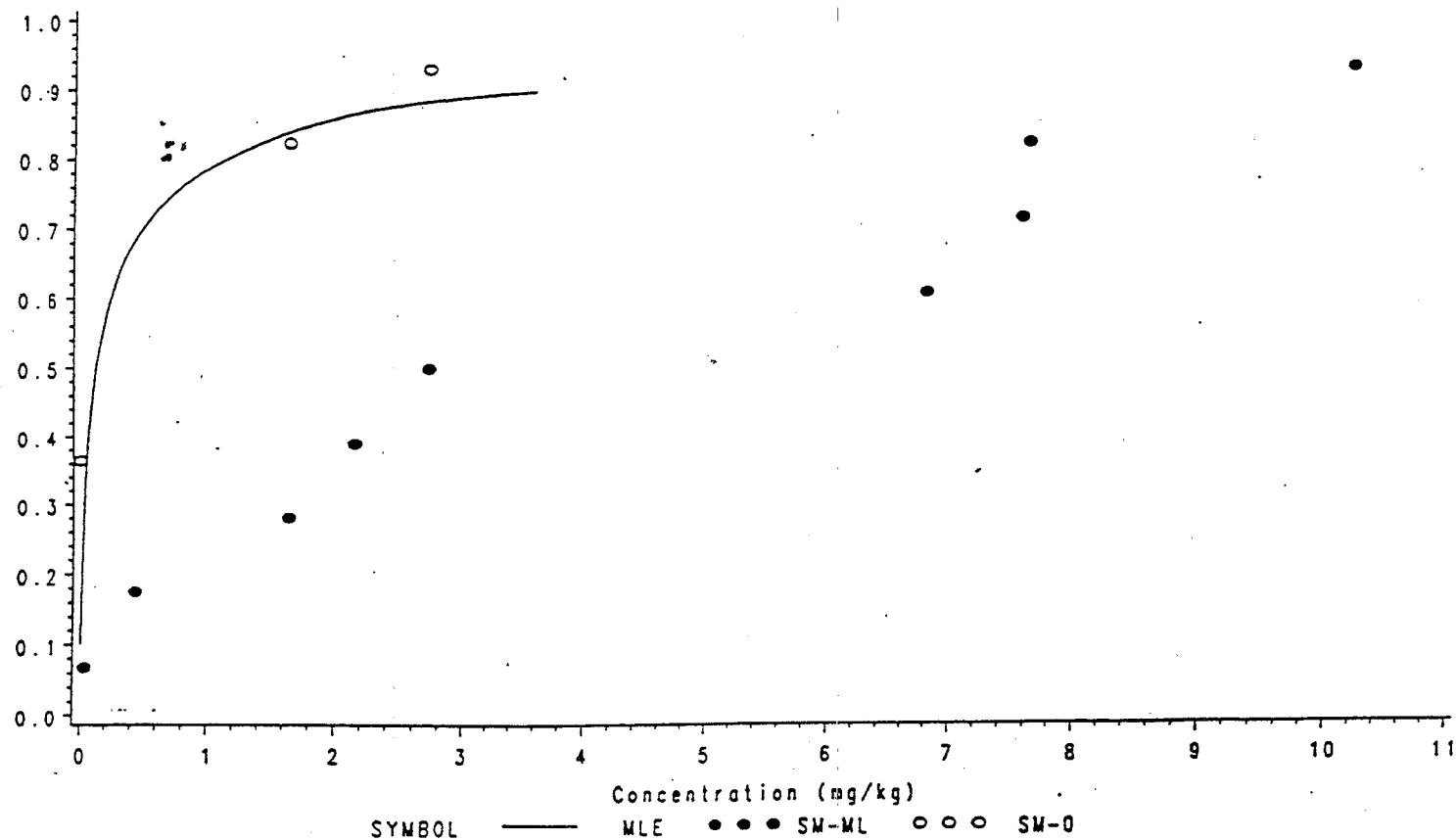
Cumulative Frequency for Total Phosphorous (mg/kg)



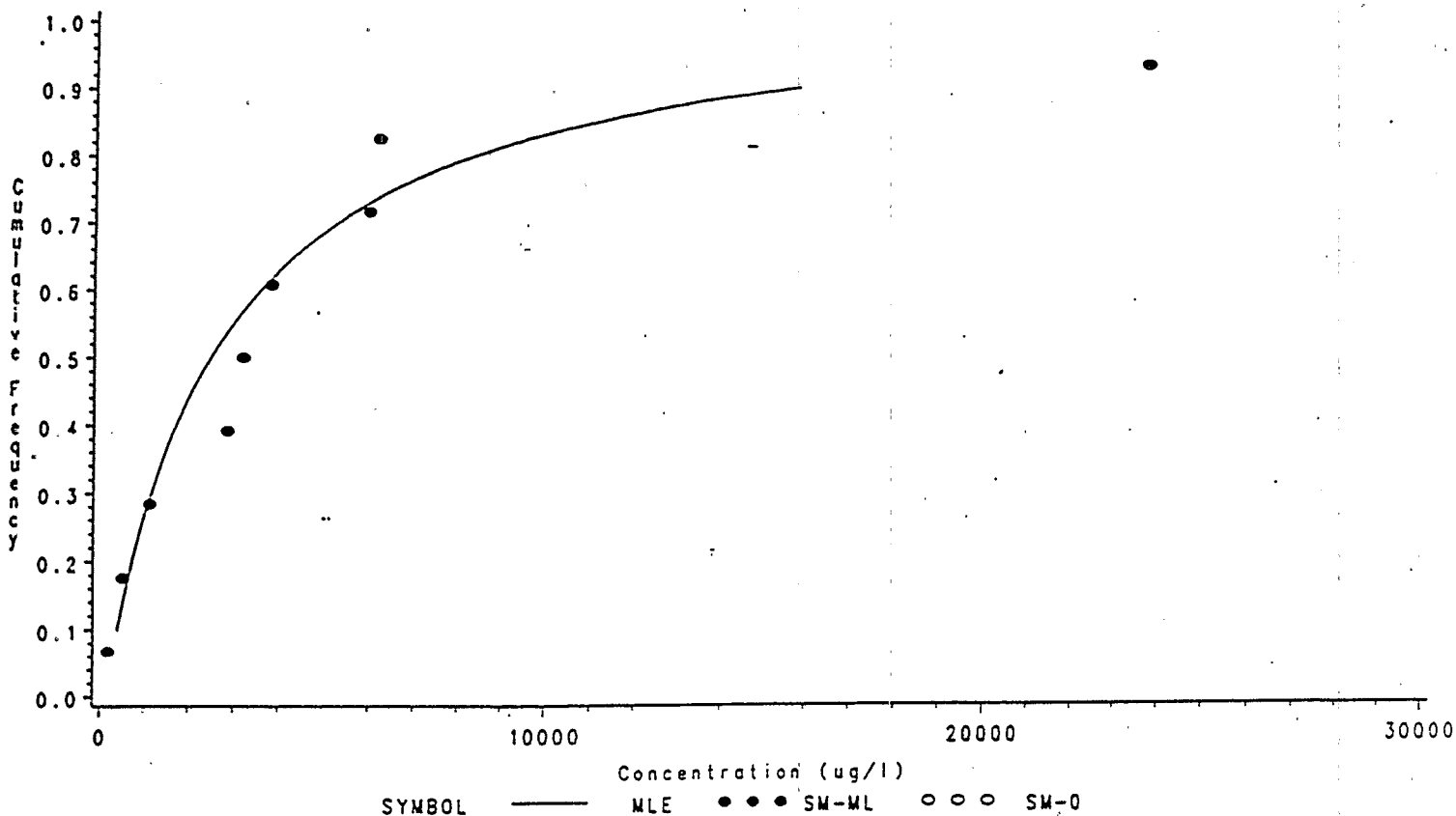
Cumulative Frequency for Selenium (ug/l)



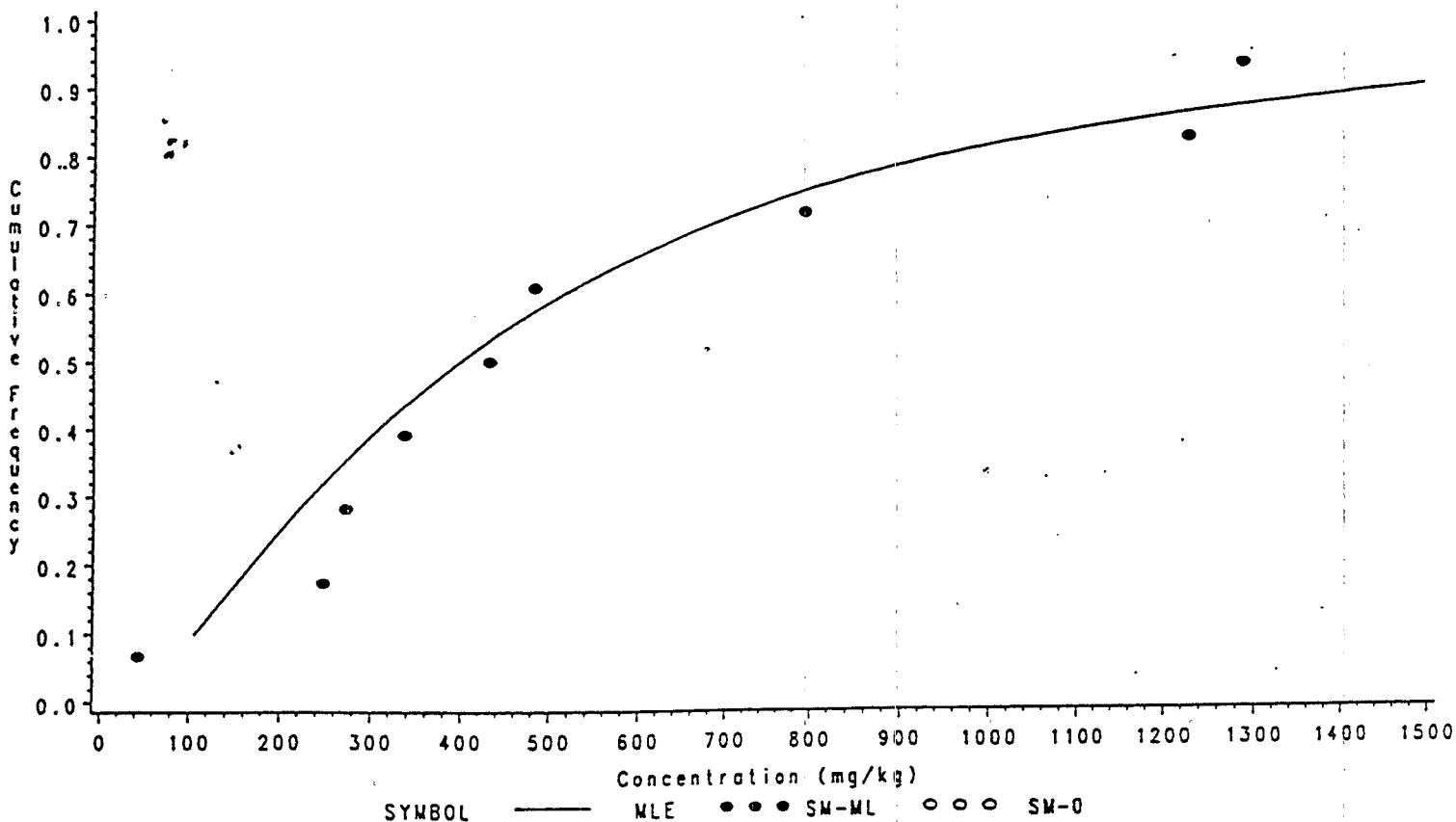
Cumulative Frequency for Selenium (mg/kg)



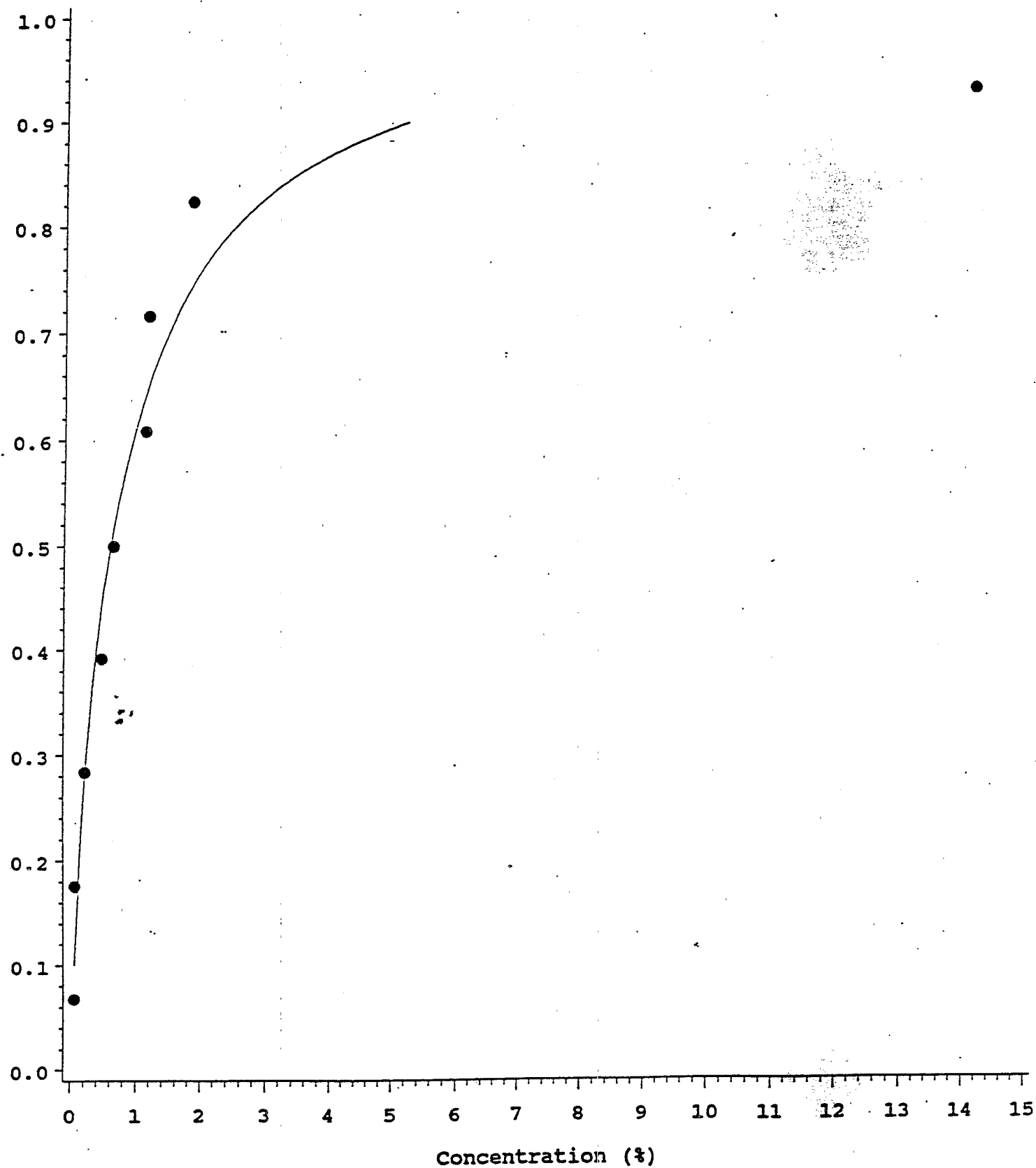
Cumulative Frequency for Zinc (ug/l)



Cumulative Frequency for Zinc (mg/kg)



Cumulative Frequency for Percent Solids (%)



SYMBOL

—

MLE

• • • SM-ML

○ ○ ○

SM-0

Appendix C

Data Listing

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=ALDRIN/DIELDRIN(TOTAL) -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.100	UG/L
19975	.	0.100	UG/L
19976	.	0.100	UG/L
19977	2.50	.	UG/L
19978	0.75	.	UG/L
19979	.	0.184	UG/L
19980	.	0.100	UG/L
19981	.	0.100	UG/L
19982	.	0.100	UG/L

----- Pollutant=ALPHA-CHLORDANE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.100	UG/L
19975	.	0.100	UG/L
19976	.	0.100	UG/L
19977	.	0.100	UG/L
19978	.	0.100	UG/L
19979	.	0.184	UG/L
19980	.	0.100	UG/L
19981	.	0.100	UG/L
19982	.	0.100	UG/L

----- Pollutant=AMMONIA (AS N) -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	45.00	.	MG/L
19975	0.48	.	MG/L
19976	40.00	.	MG/L
19977	11.00	.	MG/L
19978	45.00	.	MG/L
19979	33.00	.	MG/L
19980	56.00	.	MG/L
19981	54.00	.	MG/L
19982	100.00	.	MG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=ARSENIC -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	20.000	UG/L
19975	.	20.000	UG/L
19976	.	20.000	UG/L
19977	.	20.000	UG/L
19978	.	20.000	UG/L
19979	.	20.000	UG/L
19980	.	20.000	UG/L
19981	.	20.000	UG/L
19982	.	20.000	UG/L

----- Pollutant=BENZENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

----- Pollutant=BENZO (A) PYRENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19975	.	10.000	UG/L
19976	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=BERYLLIUM -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	5.000	UG/L
19975	.	5.000	UG/L
19976	.	5.000	UG/L
19977	.	5.000	UG/L
19978	.	5.000	UG/L
19979	.	5.000	UG/L
19980	.	5.000	UG/L
19981	.	5.000	UG/L
19982	.	5.000	UG/L

----- Pollutant=BIS(2-ETHYLHEXYL) PHTHALATE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19975	.	10.000	UG/L
19976	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

----- Pollutant=CADMIUM -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	9.40	.	UG/L
19975	.	5.000	UG/L
19976	.	5.000	UG/L
19977	.	5.000	UG/L
19978	6.40	.	UG/L
19979	18.40	.	UG/L
19980	.	5.000	UG/L
19981	.	5.000	UG/L
19982	.	5.000	UG/L

Wet Weight Concentrations of Pollutants in Septage

Pollutant=CHROMIUM

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	53.90	.	UG/L
19975	.	10.000	UG/L
19976	12.10	.	UG/L
19977	32.10	.	UG/L
19978	81.60	.	UG/L
19979	128.00	.	UG/L
19980	33.50	.	UG/L
19981	50.20	.	UG/L
19982	18.70	.	UG/L

Pollutant=COPPER

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	1340.00	.	UG/L
19975	77.10	.	UG/L
19976	80.30	.	UG/L
19977	115.00	.	UG/L
19978	758.00	.	UG/L
19979	174.00	.	UG/L
19980	1850.00	.	UG/L
19981	62.00	.	UG/L
19982	69.60	.	UG/L

Pollutant=DDT,DDE,DDD(TOTAL)

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.338	UG/L
19975	.	0.338	UG/L
19976	.	0.338	UG/L
19977	.	0.338	UG/L
19978	.	0.338	UG/L
19979	0.92	.	UG/L
19980	2.88	.	UG/L
19981	.	0.338	UG/L
19982	.	0.338	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=GAMMA-CHLORDANE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.113	UG/L
19975	.	0.113	UG/L
19976	.	0.113	UG/L
19977	.	0.113	UG/L
19978	.	0.113	UG/L
19979	.	0.207	UG/L
19980	.	0.113	UG/L
19981	.	0.113	UG/L
19982	.	0.113	UG/L

----- Pollutant=HEPTACHLOR -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	0.25	.	UG/L
19975	.	0.063	UG/L
19976	.	0.063	UG/L
19977	.	0.063	UG/L
19978	.	0.063	UG/L
19979	.	0.115	UG/L
19980	.	0.063	UG/L
19981	.	0.063	UG/L
19982	.	0.063	UG/L

----- Pollutant=HEXACHLOROBENZENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19975	.	10.000	UG/L
19976	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=HEXACHLOROBUTADIENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19975	.	10.000	UG/L
19976	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

----- Pollutant=LEAD -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	121.00	.	UG/L
19975	.	50.000	UG/L
19976	.	50.000	UG/L
19977	.	50.000	UG/L
19978	.	50.000	UG/L
19979	70.30	.	UG/L
19980	79.30	.	UG/L
19981	.	50.000	UG/L
19982	.	50.000	UG/L

----- Pollutant=LINDANE (GAMMA-BHC) -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.138	UG/L
19975	.	0.138	UG/L
19976	.	0.138	UG/L
19977	0.13	.	UG/L
19978	.	0.138	UG/L
19979	.	0.253	UG/L
19980	0.25	.	UG/L
19981	.	0.138	UG/L
19982	.	0.138	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=MERCURY -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	0.200	UG/L
19975	.	0.200	UG/L
19976	.	0.200	UG/L
19977	0.30	.	UG/L
19978	.	0.200	UG/L
19979	1.30	.	UG/L
19980	0.45	.	UG/L
19981	0.50	.	UG/L
19982	4.05	.	UG/L

----- Pollutant=MOLYBDENUM -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	14.40	.	UG/L
19975	.	10.000	UG/L
19976	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	10.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

----- Pollutant=N-NITROSODIMETHYLAMINE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	50.000	UG/L
19975	.	50.000	UG/L
19976	.	50.000	UG/L
19977	.	50.000	UG/L
19978	.	50.000	UG/L
19979	.	100.000	UG/L
19980	.	50.000	UG/L
19981	.	50.000	UG/L
19982	.	50.000	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=NICKEL -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	40.000	UG/L
19975	.	40.000	UG/L
19976	.	40.000	UG/L
19977	79.80	.	UG/L
19978	61.80	.	UG/L
19979	105.00	.	UG/L
19980	41.90	.	UG/L
19981	.	40.000	UG/L
19982	41.60	.	UG/L

----- Pollutant=NITRATE+NITRITE (AS N) -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	0.20	.	MG/L
19975	.	0.100	MG/L
19976	.	0.100	MG/L
19977	0.90	.	MG/L
19978	0.20	.	MG/L
19979	0.60	.	MG/L
19980	0.60	.	MG/L
19981	0.60	.	MG/L
19982	0.20	.	MG/L

----- Pollutant=PCB(TOTAL) -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	1.750	UG/L
19975	.	1.750	UG/L
19976	.	1.750	UG/L
19977	.	1.750	UG/L
19978	.	1.750	UG/L
19979	.	3.218	UG/L
19980	.	1.750	UG/L
19981	.	1.750	UG/L
19982	.	1.750	UG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=SELENIUM -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	50.000	UG/L
19975	.	5.000	UG/L
19976	.	5.000	UG/L
19977	.	5.000	UG/L
19978	.	5.000	UG/L
19979	30.50	.	UG/L
19980	.	5.000	UG/L
19981	.	50.000	UG/L
19982	32.00	.	UG/L

----- Pollutant=TOTAL KJELDAHL NITROGEN -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	142.00	.	MG/L
19975	9.00	.	MG/L
19976	55.00	.	MG/L
19977	31.00	.	MG/L
19978	70.00	.	MG/L
19979	119.00	.	MG/L
19980	115.00	.	MG/L
19981	175.00	.	MG/L
19982	152.00	.	MG/L

----- Pollutant=TOTAL PHOSPHOROUS -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	32.00	.	MG/L
19975	1.70	.	MG/L
19976	7.00	.	MG/L
19977	25.00	.	MG/L
19978	12.00	.	MG/L
19979	48.00	.	MG/L
19980	36.00	.	MG/L
19981	46.00	.	MG/L
19982	41.00	.	MG/L

Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=TOTAL SOLIDS -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	4880.00	.	MG/L
19975	733.00	.	MG/L
19976	653.00	.	MG/L
19977	142000.00	.	MG/L
19978	2310.00	.	MG/L
19979	18500.00	.	MG/L
19980	11300.00	.	MG/L
19981	6580.00	.	MG/L
19982	11700.00	.	MG/L

----- Pollutant=TOXAPHENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	11.375	UG/L
19975	.	11.375	UG/L
19976	.	0.910	UG/L
19977	.	11.375	UG/L
19978	.	11.375	UG/L
19979	.	20.920	UG/L
19980	.	11.375	UG/L
19981	.	11.735	UG/L
19982	.	11.375	UG/L

----- Pollutant=TRICHLOROETHENE -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	.	10.000	UG/L
19977	.	10.000	UG/L
19978	.	10.000	UG/L
19979	.	20.000	UG/L
19980	.	10.000	UG/L
19981	.	10.000	UG/L
19982	.	10.000	UG/L

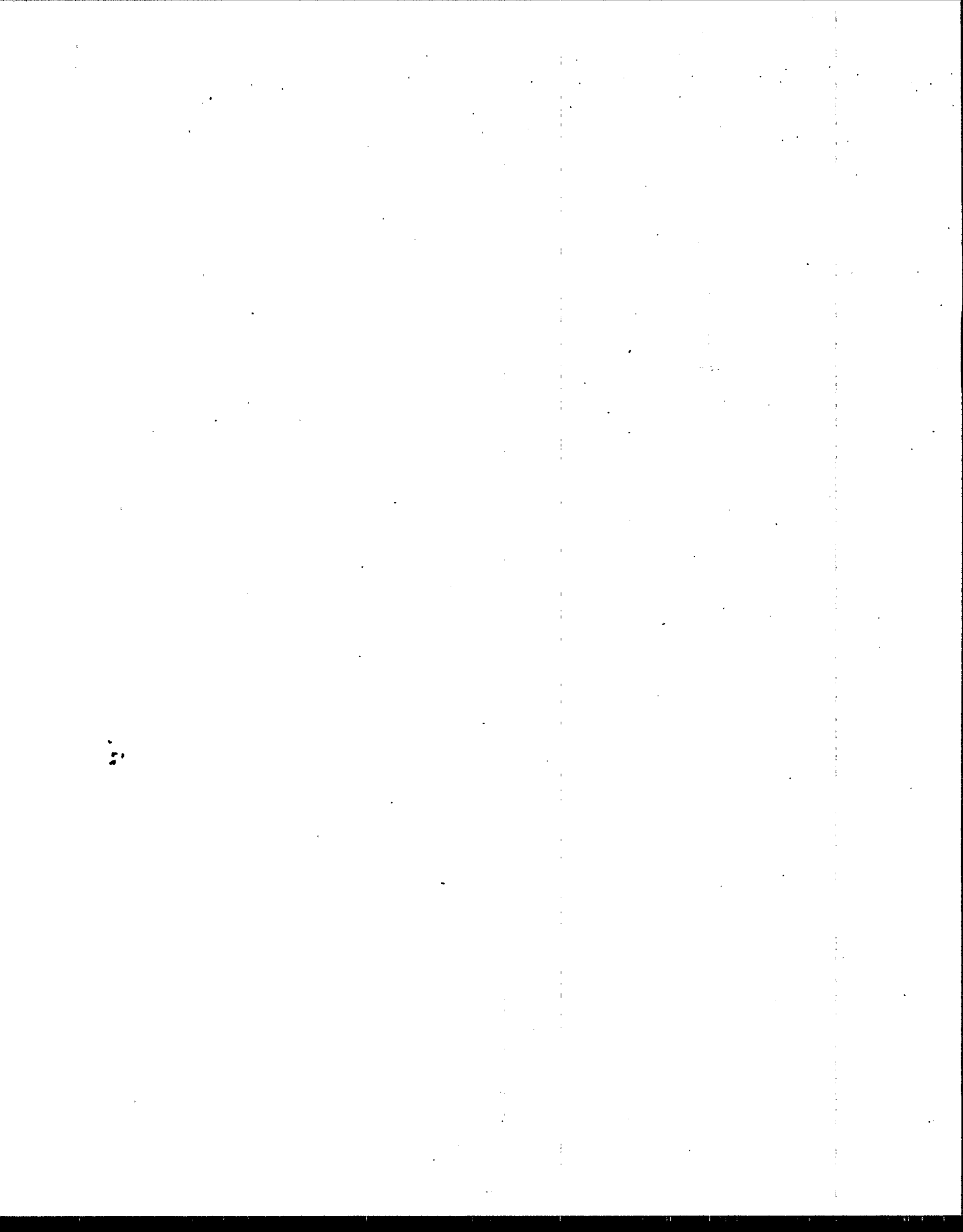
Wet Weight Concentrations of Pollutants in Septage

----- Pollutant=ZINC -----

EPA Sample Number	Quantified Amount	Minimum Level	Units
19974	5990.00	.	UG/L
19975	182.00	.	UG/L
19976	519.00	.	UG/L
19977	6210.00	.	UG/L
19978	1120.00	.	UG/L
19979	23800.00	.	UG/L
19980	3810.00	.	UG/L
19981	2850.00	.	UG/L
19982	3190.00	.	UG/L

APPENDIX F

**CALCULATION OF THE AMOUNT OF SEWAGE SLUDGE USED OR DISPOSED
FOR THE PART 503 FREQUENCY OF MONITORING REQUIREMENTS**



**CALCULATION OF THE AMOUNT OF SEWAGE SLUDGE USED OR DISPOSED
FOR THE PART 503 FREQUENCY OF MONITORING REQUIREMENTS**

**Office of Science and Technology
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460**

November 23, 1992

CALCULATION OF THE AMOUNT OF SEWAGE SLUDGE USED OR DISPOSED FOR THE PART 503 FREQUENCY OF MONITORING REQUIREMENTS

INTRODUCTION

The Standards for the Use or Disposal of Sewage Sludge in 40 CFR Part 503 contain frequency of monitoring requirements for land application of sewage sludge, placement of sewage sludge on a surface disposal site, and firing of sewage sludge in a sewage sludge incinerator. These requirements indicate how often sewage sludge has to be monitored for pollutant concentrations, pathogen densities, and vector attraction reduction. They are based on the amount of sewage sludge used or disposed during a 365 day period.

For land application, the frequency of monitoring requirements are based either on the amount of bulk sewage sludge applied to the land or the amount of sewage sludge received by a person who prepares the sewage sludge for sale or give away in a bag or similar enclosure for application to the land. As those amounts increase, the frequency of monitoring increases.

For surface disposal and firing of sewage sludge in a sewage sludge incinerator, the frequency of monitoring requirements are based on the amount of sewage sludge placed on a surface disposal site and the amount of sewage sludge fired in a sewage sludge incinerator, respectively. For these two practices, the frequency of monitoring also increases as the amount of sewage sludge used or disposed increases.

This document discusses calculation of the amounts of sewage sludge used or disposed for the Part 503 frequency of monitoring requirements. The assumptions on which those requirements are based and the calculations for the amounts used or disposed are presented below. Also presented below are the Part 503 frequency of monitoring requirements.

ASSUMPTIONS

- o Wastewater is treated in "typical" secondary wastewater treatment plant (i.e., primary settling followed by biological treatment followed by secondary settling).
- o Sewage sludge is stabilized in an anaerobic digester prior to use or disposal.
- o Influent wastewater BOD5 concentration = 200 mg/l.
- o Effluent wastewater BOD5 concentration = 30 mg/l.
- o Influent wastewater TSS concentration = 200 mg/l.
- o Effluent wastewater TSS concentration = 30 mg/l.

- o TSS percent removal in primary treatment process = 60.
- o Percent volatile solids in the influent to digester = 60.
- o Percent volatile solids reduction in digester = 38.
- o Percent fixed solids in the influent to digester = 40
- o Solids concentration factor during secondary settling = 0.9

CALCULATIONS FOR TREATMENT WORKS WITH A FLOW RATE OF ONE MGD

- o TSS removal in primary treatment process:

Influent TSS x Flow rate x Conversion factor x Percent removal

$$200 \text{ mg/l} \times 1 \text{ MGD} \times 8.34 \times 0.6 = \underline{1,000 \text{ pounds per day.}}$$

- o BOD5 removal through secondary settling process:

$$\text{Influent BOD5} - \text{Effluent BOD5} = 200 - 30 = 170 \text{ mg/l}$$

Concentration removed x Flow rate x Conv. fact. x Conc. fact.

$$170 \text{ mg/l} \times 1 \text{ MGD} \times 8.34 \times 0.9 = \underline{1,276 \text{ pounds per day.}}$$

- o Sewage sludge to the digester:

Primary settling sludge + secondary settling sludge = total

$$1,000 + 1,276 = \underline{2,276 \text{ pounds per day.}}$$

- o Amount of sewage sludge used or disposed:

Fixed solids = total amount x percent of total solids.

$$\text{Fixed solids} = 2,276 \times 0.4 = \underline{910 \text{ pounds per day.}}$$

Volatile solids = total amount x percent of total solids x percent remaining after digestion.

$$\text{Volatile solids} = 2,276 \times 0.6 \times (1.0 - 0.38) = \underline{847 \text{ pounds/day}}$$

Total amount used or disposed = Fixed solids + volatile solids

$$910 + 847 = \underline{1,757 \text{ pounds per day}}$$

$$\text{Total amount} = \frac{1,757 \text{ pounds}}{\text{days}} \times \frac{365 \text{ days}}{\text{year}} \times \frac{1 \text{ metric ton}}{2,200 \text{ pounds}}$$

$$\text{Total amount for 1 MGD} = \underline{292 \text{ metric tons per year.}}$$

Report amount in two significant figures:

Use 290 metric tons per year for 1 MGD treatment works (dry weight basis)

CALCULATION FOR A TREATMENT WORKS WITH A FLOW RATE OF FIVE MGD

Total amount = Amount for 1 MGD treatment works times 5

Total amount = $290 \times 5 = 1,450$ metric tons per year

Report amount in two significant figures:

Use 1,500 metric tons per year for five MGD treatment works (dry weight basis)

CALCULATION FOR A TREATMENT WORKS WITH A FLOW RATE OF 50 MGD

Total amount = Amount for 1 MGD treatment works x 50

Total amount = $290 \times 50 = 14,500$ metric tons per year

Report amount in two significant figures:

Use 15,000 metric tons per year for 50 MGD treatment works (dry weight basis)

PART 503 FREQUENCY OF MONITORING REQUIREMENTS

Results of the above calculations were used as the basis for the frequency of monitoring requirements in Part 503. Those frequencies are presented below.

FREQUENCY OF MONITORING

<u>Amount of sewage sludge used or disposed (metric tons per 365 day period-dry weight)</u>	<u>Frequency</u>
Greater than zero but less than 290	once per year
Equal to or greater than 290 but less than 1,500	once per quarter (four times per year)
Equal to or greater than 1,500 but less than 15,000	once per 60 days (six time per year)
Equal to or greater than 15,000	once per month (12 times per year)