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Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Phenanthrene

PREFACE

This document is one of a series of preliminary assessments dealing with chemicals of potential concern in municipal sewage sludge. The purpose of these documents is to: (a) summarize the available data for the constituents of potential concern, (b) identify the key environmental pathways for each constituent related to a reuse and disposal option (based on hazard indices), and (c) evaluate the conditions under which such a pollutant may pose a hazard. Each document provides a scientific basis for making an initial determination of whether a pollutant, at levels currently observed in sludges, poses a likely hazard to human health or the environment when sludge is disposed of by any of several methods. These methods include landspreading on food chain or nonfood chain crops, distribution and marketing programs, landfilling, incineration and ocean disposal.

These documents are intended to serve as a rapid screening tool to narrow an initial list of pollutants to those of concern. If a significant hazard is indicated by this preliminary analysis, a more detailed assessment will be undertaken to better quantify the risk from this chemical and to derive criteria if warranted. If a hazard is shown to be unlikely, no further assessment will be conducted at this time; however, a reassessment will be conducted after initial regulations are finalized. In no case, however, will criteria be derived solely on the basis of information presented in this document.

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SECTION 1

INTRODUCTION

This preliminary data profile is one of a series of profiles dealing with chemical pollutants potentially of concern in municipal sewage sludges. Phenanthrene (PA) was initially identified as being of potential concern when sludge is placed in a landfill, incinerated or ocean disposed.* This profile is a compilation of information that may be useful in determining whether PA poses an actual hazard to human health or the environment when sludge is disposed of by these methods.

The focus of this document is the calculation of "preliminary hazard indices" for selected potential exposure pathways, as shown in Section 3. Each index illustrates the hazard that could result from movement of a pollutant by a given pathway to cause a given effect (e.g., sludge → groundwater → human toxicity). The values and assumptions employed in these calculations tend to represent a reasonable "worst case"; analysis of error or uncertainty has been conducted to a limited degree. The resulting value in most cases is indexed to unity; i.e., values >1 may indicate a potential hazard, depending upon the assumptions of the calculation.

The data used for index calculation have been selected or estimated based on information presented in the "preliminary data profile", Section 4. Information in the profile is based on a compilation of the recent literature. An attempt has been made to fill out the profile outline to the greatest extent possible. However, since this is a preliminary analysis, the literature has not been exhaustively perused.

The "preliminary conclusions" drawn from each index in Section 3 are summarized in Section 2. The preliminary hazard indices will be used as a screening tool to determine which pollutants and pathways may pose a hazard. Where a potential hazard is indicated by interpretation of these indices, further analysis will include a more detailed examination of potential risks as well as an examination of site-specific factors. These more rigorous evaluations may change the preliminary conclusions presented in Section 2, which are based on a reasonable "worst case" analysis.

The preliminary hazard indices for selected exposure routes pertinent to landfilling, incineration and ocean disposal practices are included in this profile. The calculation formulae for these indices are shown in the Appendix. The indices are rounded to two significant figures.

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* Listings were determined by a series of expert workshops convened during March-May, 1984 by the Office of Water Regulations and Standards (OWRS) to discuss landspreading, landfilling, incineration, and ocean disposal, respectively, of municipal sewage sludge.

SECTION 2

PRELIMINARY CONCLUSIONS FOR PHENANTHRENE IN MUNICIPAL SEWAGE SLUDGE

The following preliminary conclusions have been derived from the calculation of "preliminary hazard indices", which represent conservative or "worst case" analyses of hazard. The indices and their basis and interpretation are explained in Section 3. Their calculation formulae are shown in the Appendix.

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

II. LANDFILLING

Landfilled sludge may slightly increase the groundwater concentration of PA at the well; this increase may be substantial when all worst-case conditions prevail at a disposal site (see Index 1). The human cancer risk due to PA resulting from groundwater contamination could not be determined due to lack of data (see Index 2).

III. INCINERATION

Incineration of sludge may cause substantial increases in the concentration of PA in air (see Index 1). The human cancer risk due to PA resulting from inhalation of incinerator emissions could not be evaluated due to lack of data (see Index 2).

IV. OCEAN DISPOSAL

Slight increases in seawater concentration of PA occur when sludges are disposed at the typical site, but greater increases occur when sludges are dumped at the worst site (see Index 1). After a 24-hour dumping cycle, increases occur in the seawater concentration of PA for all scenarios evaluated (see Index 2). Only slight increases of incremental hazard to aquatic life occur for all of the scenarios evaluated (see Index 3). A conclusion was not drawn as to the cancer risk resulting from seafood consumption because the index values were not calculated due to lack of data (see Index 4).

SECTION 3

PRELIMINARY HAZARD INDICES FOR PHENANTHRENE IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

II. LANDFILLING

A. Index of Groundwater Concentration Resulting from Landfilled Sludge (Index 1)

1. **Explanation** - Calculates groundwater contamination which could occur in a potable aquifer in the landfill vicinity. Uses U.S. EPA's Exposure Assessment Group (EAG) model, "Rapid Assessment of Potential Groundwater Contamination Under Emergency Response Conditions" (U.S. EPA, 1983a). Treats landfill leachate as a pulse input, i.e., the application of a constant source concentration for a short time period relative to the time frame of the analysis. In order to predict pollutant movement in soils and groundwater, parameters regarding transport and fate, and boundary or source conditions are evaluated. Transport parameters include the interstitial pore water velocity and dispersion coefficient. Pollutant fate parameters include the degradation/decay coefficient and retardation factor. Retardation is primarily a function of the adsorption process, which is characterized by a linear, equilibrium partition coefficient representing the ratio of adsorbed and solution pollutant concentrations. This partition coefficient, along with soil bulk density and volumetric water content, are used to calculate the retardation factor. A computer program (in FORTRAN) was developed to facilitate computation of the analytical solution. The program predicts pollutant concentration as a function of time and location in both the unsaturated and saturated zone. Separate computations and parameter estimates are required for each zone. The prediction requires evaluations of four dimensionless input values and subsequent evaluation of the result, through use of the computer program.

2. **Assumptions/Limitations** - Conservatively assumes that the pollutant is 100 percent mobilized in the leachate and that all leachate leaks out of the landfill in a finite period and undiluted by precipitation. Assumes that all soil and aquifer properties are homogeneous and isotropic throughout each zone; steady, uniform flow occurs only in

the vertical direction throughout the unsaturated zone, and only in the horizontal (longitudinal) plane in the saturated zone; pollutant movement is considered only in direction of groundwater flow for the saturated zone; all pollutants exist in concentrations that do not significantly affect water movement; for organic chemicals, the background concentration in the soil profile or aquifer prior to release from the source is assumed to be zero; the pollutant source is a pulse input; no dilution of the plume occurs by recharge from outside the source area; the leachate is undiluted by aquifer flow within the saturated zone; concentration in the saturated zone is attenuated only by dispersion.

3. Data Used and Rationale

a. Unsaturated zone

i. Soil type and characteristics

(a) Soil type

Typical	Sandy loam
Worst	Sandy

These two soil types were used by Gerritse et al. (1982) to measure partitioning of elements between soil and a sewage sludge solution phase. They are used here since these partitioning measurements (i.e., K_d values) are considered the best available for analysis of metal transport from landfilled sludge. The same soil types are also used for nonmetals for convenience and consistency of analysis.

(b) Dry bulk density (P_{dry})

Typical	1.53 g/mL
Worst	1.925 g/mL

Bulk density is the dry mass per unit volume of the medium (soil), i.e., neglecting the mass of the water (Camp Dresser and McKee, Inc. (CDM), 1984a).

(c) Volumetric water content (θ)

Typical	0.195 (unitless)
Worst	0.133 (unitless)

The volumetric water content is the volume of water in a given volume of media, usually expressed as a fraction or percent. It depends on properties of the media and the water flux estimated by infiltration or net recharge. The

volumetric water content is used in calculating the water movement through the unsaturated zone (pore water velocity) and the retardation coefficient. Values obtained from CDM, 1984a.

(d) **Fraction of organic carbon (f_{oc})**

Typical	0.005	(unitless)
Worst	0.0001	(unitless)

Organic content of soils is described in terms of percent organic carbon, which is required in the estimation of partition coefficient, K_d. Values, obtained from R. Griffin (1984) are representative values for subsurface soils.

ii. **Site parameters**

(a) **Landfill leaching time (LT)** = 5 years

Sikora et al. (1982) monitored several sludge entrenchment sites throughout the United States and estimated time of landfill leaching to be 4 or 5 years. Other types of landfills may leach for longer periods of time; however, the use of a value for entrenchment sites is conservative because it results in a higher leachate generation rate.

(b) **Leachate generation rate (Q)**

Typical	0.8 m/year
Worst	1.6 m/year

It is conservatively assumed that sludge leachate enters the unsaturated zone undiluted by precipitation or other recharge, that the total volume of liquid in the sludge leaches out of the landfill, and that leaching is complete in 5 years. Landfilled sludge is assumed to be 20 percent solids by volume, and depth of sludge in the landfill is 5 m in the typical case and 10 m in the worst case. Thus, the initial depth of liquid is 4 and 8 m, and average yearly leachate generation is 0.8 and 1.6 m, respectively.

(c) **Depth to groundwater (h)**

Typical	5 m
Worst	0 m

Eight landfills were monitored throughout the United States and depths to groundwater below

them were listed. A typical depth to groundwater of 5 m was observed (U.S. EPA, 1977). For the worst case, a value of 0 m is used to represent the situation where the bottom of the landfill is occasionally or regularly below the water table. The depth to groundwater must be estimated in order to evaluate the likelihood that pollutants moving through the unsaturated soil will reach the groundwater.

(d) Dispersivity coefficient (α)

Typical	0.5 m
Worst	Not applicable

The dispersion process is exceedingly complex and difficult to quantify, especially for the unsaturated zone. It is sometimes ignored in the unsaturated zone, with the reasoning that pore water velocities are usually large enough so that pollutant transport by convection, i.e., water movement, is paramount. As a rule of thumb, dispersivity may be set equal to 10 percent of the distance measurement of the analysis (Gelhar and Axness, 1981). Thus, based on depth to groundwater listed above, the value for the typical case is 0.5 and that for the worst case does not apply since leachate moves directly to the unsaturated zone.

iii. Chemical-specific parameters

(a) Sludge concentration of pollutant (SC)

Typical	3.709 mg/kg DW
Worst	20.69 mg/kg DW

The typical and worst sludge concentrations were statistically derived from data presented in a survey of sludges from publicly-owned treatment works (POTWs) throughout the United States (U.S. EPA, 1982) and represent the 50th and 95th percentiles, respectively. (See Section 4, p. 4-1.)

(b) Soil half-life of pollutant ($t_{\frac{1}{2}}$) - Data not immediately available.

PA belongs to a class of compounds referred to as polycyclic aromatic hydrocarbons (PAHs). Soil half-lives of PAHs may range from less than one day to several years (U.S. EPA, 1984a). (See Section 4, p. 4-2.)

(c) **Degradation rate (μ) = 0 day^{-1}**

The unsaturated zone can serve as an effective medium for reducing pollutant concentration through a variety of chemical and biological decay mechanisms which transform or attenuate the pollutant. While these decay processes are usually complex, they are approximated here by a first-order rate constant. The degradation rate is calculated using the following formula:

$$\mu = \frac{0.693}{t_{\frac{1}{2}}}$$

Since data is not available for the half-life of the pollutant, the degradation rate is conservatively assumed to be zero.

(d) **Organic carbon partition coefficient (K_{oc}) = 23,000 mL/g**

The organic carbon partition coefficient is multiplied by the percent organic carbon content of soil (f_{oc}) to derive a partition coefficient (K_d), which represents the ratio of absorbed pollutant concentration to the dissolved (or solution) concentration. The equation (K_{oc} x f_{oc}) assumes that organic carbon in the soil is the primary means of adsorbing organic compounds onto soils. This concept serves to reduce much of the variation in K_d values for different soil types. The value of K_{oc} is from Hassett et al. (1983). (See Section 4, p. 4-5.)

b. Saturated zone

i. Soil type and characteristics

(a) **Soil type**

Typical	Silty sand
Worst	Sand

A silty sand having the values of aquifer porosity and hydraulic conductivity defined below represents a typical aquifer material. A more conductive medium such as sand transports the plume more readily and with less dispersion and therefore represents a reasonable worst case.

(b) **Aquifer porosity (Ø)**

Typical 0.44 (unitless)
Worst 0.389 (unitless)

Porosity is that portion of the total volume of soil that is made up of voids (air) and water. Values corresponding to the above soil types are from Pettyjohn et al. (1982) as presented in U.S. EPA (1983a).

(c) **Hydraulic conductivity of the aquifer (K)**

Typical 0.86 m/day
Worst 4.04 m/day

The hydraulic conductivity (or permeability) of the aquifer is needed to estimate flow velocity based on Darcy's Equation. It is a measure of the volume of liquid that can flow through a unit area or media with time; values can range over nine orders of magnitude depending on the nature of the media. Heterogenous conditions produce large spatial variation in hydraulic conductivity, making estimation of a single effective value extremely difficult. Values used are from Freeze and Cherry (1979) as presented in U.S. EPA (1983a).

(d) **Fraction of organic carbon (f_{oc}) =** 0.0 (unitless)

Organic carbon content, and therefore adsorption, is assumed to be 0 in the saturated zone.

ii. **Site parameters**

(a) **Average hydraulic gradient between landfill and well (i)**

Typical 0.001 (unitless)
Worst 0.02 (unitless)

The hydraulic gradient is the slope of the water table in an unconfined aquifer, or the piezometric surface for a confined aquifer. The hydraulic gradient must be known to determine the magnitude and direction of groundwater flow. As gradient increases, dispersion is reduced. Estimates of typical and high gradient values were provided by Donigian (1985).

(b) **Distance from well to landfill ($\Delta\ell$)**

Typical	100 m
Worst	50 m

This distance is the distance between a landfill and any functioning public or private water supply or livestock water supply.

(c) **Dispersivity coefficient (α)**

Typical	10 m
Worst	5 m

These values are 10 percent of the distance from well to landfill ($\Delta\ell$), which is 100 and 50 m, respectively, for typical and worst conditions.

(d) **Minimum thickness of saturated zone (B) = 2 m**

The minimum aquifer thickness represents the assumed thickness due to preexisting flow; i.e., in the absence of leachate. It is termed the minimum thickness because in the vicinity of the site it may be increased by leachate infiltration from the site. A value of 2 m represents a worst case assumption that preexisting flow is very limited and therefore dilution of the plume entering the saturated zone is negligible.

(e) **Width of landfill (W) = 112.8 m**

The landfill is arbitrarily assumed to be circular with an area of 10,000 m^2.

iii. **Chemical-specific parameters**

(a) **Degradation rate (μ) = 0 day^{-1}**

Degradation is assumed not to occur in the saturated zone.

(b) **Background concentration of pollutant in groundwater (BC) = 0 $\mu g/L$**

It is assumed that no pollutant exists in the soil profile or aquifer prior to release from the source.

4. **Index Values** - See Table 3-1.

5. **Value Interpretation** - Value equals the maximum expected groundwater concentration of pollutant, in μg/L, at the well.

6. **Preliminary Conclusion** - Landfilled sludge may slightly increase the groundwater concentration of PA at the well; this increase may be substantial when all worst-case conditions prevail at a disposal site.

B. **Index of Human Cancer Risk Resulting from Groundwater Contamination (Index 2)**

1. **Explanation** - Calculates human exposure which could result from groundwater contamination. Compares exposure with cancer risk-specific intake (RSI) of pollutant.

2. **Assumptions/Limitations** - Assumes long-term exposure to maximum concentration at well at a rate of 2 L/day.

3. **Data Used and Rationale**

   a. **Index of groundwater concentration resulting from landfilled sludge (Index 1)**

      See Section 3, p. 3-9.

   b. **Average human consumption of drinking water (AC)** = 2 L/day

      The value of 2 L/day is a standard value used by U.S. EPA in most risk assessment studies.

   c. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

   d. **Cancer potency** - Data not immediately available.

   e. **Cancer risk-specific intake (RSI)** - Data not immediately available.

4. **Index 2 Values** - Values were not calculated due to lack of data.

5. **Value Interpretation** - Value >1 indicates a potential increase in cancer risk of 10^{-6} (1 in 1,000,000) due only to groundwater contaminated by landfill. The value does not account for the possible increase in risk resulting from daily dietary intake of pollutant since DI data were not immediately available.

6. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

TABLE 3-1. INDEX OF GROUNDWATER CONCENTRATION RESULTING FROM LANDFILLED SLUDGE (INDEX 1) AND INDEX OF HUMAN CANCER RISK RESULTING FROM GROUNDWATER CONTAMINATION (INDEX 2)

Site Characteristics	Condition of Analysis[a,b,c] 1	2	3	4	5	6	7	8
Sludge concentration	T	W	T	T	T	T	W	N
Unsaturated Zone								
Soil type and characteristics[d]	T	T	W	NA	T	T	NA	N
Site parameters[e]	T	T	T	W	T	T	W	N
Saturated Zone								
Soil type and characteristics[f]	T	T	T	T	W	T	W	N
Site parameters[g]	T	T	T	T	T	W	W	N
Index 1 Value (μg/L)	0.101	0.563	0.101	0.101	0.532	3.29	120.0	0
Index 2 Value	NC[h]	NC	NC	NC	NC	NC	NC	NC

[a]T = Typical values used; W = worst-case values used; N = null condition, where no landfill exists, used as basis for comparison; NA = not applicable for this condition.

[b]Index values for combinations other than those shown may be calculated using the formulae in the Appendix.

[c]See Table A-1 in Appendix for parameter values used.

[d]Dry bulk density (P_{dry}), volumetric water content (θ), and fraction of organic carbon (f_{oc}).

[e]Leachate generation rate (Q), depth to groundwater (h), and dispersivity coefficient (α).

[f]Aquifer porosity ($\emptyset$) and hydraulic conductivity of the aquifer (K).

[g]Hydraulic gradient (i), distance from well to landfill ($\Delta\ell$), and dispersivity coefficient (α).

[h]NC = Not calculated due to lack of data.

III. INCINERATION

A. Index of Air Concentration Increment Resulting from Incinerator Emissions (Index 1)

1. **Explanation** - Shows the degree of elevation of the pollutant concentration in the air due to the incineration of sludge. An input sludge with thermal properties defined by the energy parameter (EP) was analyzed using the BURN model (CDM, 1984a). This model uses the thermodynamic and mass balance relationships appropriate for multiple hearth incinerators to relate the input sludge characteristics to the stack gas parameters. Dilution and dispersion of these stack gas releases were described by the U.S. EPA's Industrial Source Complex Long-Term (ISCLT) dispersion model from which normalized annual ground level concentrations were predicted (U.S. EPA, 1979). The predicted pollutant concentration can then be compared to a ground level concentration used to assess risk.

2. **Assumptions/Limitations** - The fluidized bed incinerator was not chosen due to a paucity of available data. Gradual plume rise, stack tip downwash, and building wake effects are appropriate for describing plume behavior. Maximum hourly impact values can be translated into annual average values.

3. **Data Used and Rationale**

   a. **Coefficient to correct for mass and time units (C) =** 2.78×10^{-7} hr/sec x g/mg

   b. **Sludge feed rate (DS)**

      i. **Typical** = 2660 kg/hr (dry solids input)

      A feed rate of 2660 kg/hr DW represents an average dewatered sludge feed rate into the furnace. This feed rate would serve a community of approximately 400,000 people. This rate was incorporated into the U.S. EPA-ISCLT model based on the following input data:

      EP = 360 lb H_2O/mm BTU
      Combustion zone temperature - 1400°F
      Solids content - 28%
      Stack height - 20 m
      Exit gas velocity - 20 m/s
      Exit gas temperature - 356.9°K (183°F)
      Stack diameter - 0.60 m

ii. **Worst** = 10,000 kg/hr (dry solids input)

A feed rate of 10,000 kg/hr DW represents a higher feed rate and would serve a major U.S. city. This rate was incorporated into the U.S. EPA-ISCLT model based on the following input data:

EP = 392 lb H_2O/mm BTU
Combustion zone temperature - 1400°F
Solids content - 26.6%
Stack height - 10 m
Exit gas velocity - 10 m/s
Exit gas temperature - 313.8°K (105°F)
Stack diameter - 0.80 m

c. **Sludge concentration of pollutant (SC)**

Typical	3.709 mg/kg DW
Worst	20.69 mg/kg DW

See Section 3, p. 3-4.

d. **Fraction of pollutant emitted through stack (FM)**

Typical	0.05 (unitless)
Worst	0.20 (unitless)

These values were chosen as best approximations of the fraction of pollutant emitted through stacks (Farrell, 1984). No data was available to validate these values; however, U.S. EPA is currently testing incinerators for organic emissions.

e. **Dispersion parameter for estimating maximum annual ground level concentration (DP)**

Typical	3.4 $\mu g/m^3$
Worst	16.0 $\mu g/m^3$

The dispersion parameter is derived from the U.S. EPA-ISCLT short-stack model.

f. **Background concentration of pollutant in urban air (BA)** = 0.000061 $\mu g/m^3$

The atmospheric range of PA in a number of U.S. cities was reported to be 0.011 to 0.340 ng/m^3 (U.S. EPA, 1980). The geometric mean of the reported range is used as the background concentration. (See Section 4, p. 4-2.)

4. **Index 1 Values**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	1	8.64	136
	Worst	1	43.6	755
Worst	Typical	1	31.6	542
	Worst	1	172	3020

[a] The typical (3.4 $\mu g/m^3$) and worst (16.0 $\mu g/m^3$) dispersion parameters will always correspond, respectively, to the typical (2660 kg/hr DW) and worst (10,000 kg/hr DW) sludge feed rates.

5. **Value Interpretation** - Value equals factor by which expected air concentration exceeds background levels due to incinerator emissions.

6. **Preliminary Conclusion** - Incineration of sludge may cause substantial increases in the concentration of PA in air.

B. **Index of Human Cancer Risk Resulting from Inhalation of Incinerator Emissions (Index 2)**

1. **Explanation** - Shows the increase in human intake expected to result from the incineration of sludge. Ground level concentrations for carcinogens typically were developed based upon assessments published by the U.S. EPA Carcinogen Assessment Group (CAG). These ambient concentrations reflect a dose level which, for a lifetime exposure, increases the risk of cancer by 10^{-6}. For non-carcinogens, levels typically were derived from the American Conference of Government Industrial Hygienists (ACGIH) threshold limit values (TLVs) for the workplace.

2. **Assumptions/Limitations** - The exposed population is assumed to reside within the impacted area for 24 hours/day. A respiratory volume of 20 m^3/day is assumed over a 70-year lifetime.

3. **Data Used and Rationale**

a. **Index of air concentration increment resulting from incinerator emissions (Index 1)**

See Section 3, p. 3-12.

b. **Background concentration of pollutant in urban air (BA)** = 0.000061 $\mu g/m^3$

See Section 3, p. 3-11.

c. **Cancer potency** - Data not immediately available.

d. **Exposure criterion (EC)** - Data not immediately available.

A lifetime exposure level which would result in a 10^{-6} cancer risk was selected as ground level concentration against which incinerator emissions are compared. The risk estimates developed by CAG are defined as the lifetime incremental cancer risk in a hypothetical population exposed continuously throughout their lifetime to the stated concentration of the carcinogenic agent. The exposure criterion is calculated using the following formula:

$$EC = \frac{10^{-6} \times 10^{3}\ \mu g/mg \times 70\ kg}{\text{Cancer potency} \times 20\ m^3/day}$$

4. **Index 2 Values** - Values were not calculated due to lack of data.

5. **Value Interpretation** - Value > 1 indicates a potential increase in cancer risk of > 10^{-6} (1 per 1,000,000). Comparison with the null index value at 0 kg/hr DW indicates the degree to which any hazard is due to sludge incineration, as opposed to background urban air concentration.

6. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

IV. OCEAN DISPOSAL

For the purpose of evaluating pollutant effects upon and/or subsequent uptake by marine life as a result of sludge disposal, two types of mixing were modeled. The initial mixing or dilution shortly after dumping of a single load of sludge represents a high, pulse concentration to which organisms may be exposed for short time periods but which could be repeated frequently; i.e., every time a recently dumped plume is encountered. A subsequent addi-

tional degree of mixing can be expressed by a further dilution. This is defined as the average dilution occurring when a day's worth of sludge is dispersed by 24 hours of current movement and represents the time-weighted average exposure concentration for organisms in the disposal area. This dilution accounts for 8 to 12 hours of the high pulse concentration encountered by the organisms during daylight disposal operations and 12 to 16 hours of recovery (ambient water concentration) during the night when disposal operations are suspended.

A. Index of Seawater Concentration Resulting from Initial Mixing of Sludge (Index 1)

1. **Explanation** - Calculates increased concentrations in µg/L of pollutant in seawater around an ocean disposal site assuming initial mixing.

2. **Assumptions/Limitations** - Assumes that the background seawater concentration of pollutant is unknown or zero. The index also assumes that disposal is by tanker and that the daily amount of sludge disposed is uniformly distributed along a path transversing the site and perpendicular to the current vector. The initial dilution volume is assumed to be determined by path length, depth to the pycnocline (a layer separating surface and deeper water masses), and an initial plume width defined as the width of the plume four hours after dumping. The seasonal disappearance of the pycnocline is not considered.

3. **Data Used and Rationale**

   a. **Disposal conditions**

	Sludge Disposal Rate (SS)	Sludge Mass Dumped by a Single Tanker (ST)	Length of Tanker Path (L)
Typical	825 mt DW/day	1600 mt WW	8000 m
Worst	1650 mt DW/day	3400 mt WW	4000 m

The typical value for the sludge disposal rate assumes that 7.5 x 10^6 mt WW/year are available for dumping from a metropolitan coastal area. The conversion to dry weight assumes 4 percent solids by weight. The worst-case value is an arbitrary doubling of the typical value to allow for potential future increase.

The assumed disposal practice to be followed at the model site representative of the typical case is a modification of that proposed for sludge disposal at the formally designated 12-mile site in the New York Bight Apex (City of New York, 1983). Sludge barges with capacities of 3400 mt WW would be required to

discharge a load in no less than 53 minutes traveling at a minimum speed of 5 nautical miles (9260 m) per hour. Under these conditions, the barge would enter the site, discharge the sludge over 8180 m and exit the site. Sludge barges with capacities of 1600 mt WW would be required to discharge a load in no less than 32 minutes traveling at a minimum speed of 8 nautical miles (14,816 m) per hour. Under these conditions, the barge would enter the site, discharge the sludge over 7902 m and exit the site. The mean path length for the large and small tankers is 8041 m or approximately 8000 m. Path length is assumed to lie perpendicular to the direction of prevailing current flow. For the typical disposal rate (SS) of 825 mt DW/day, it is assumed that this would be accomplished by a mixture of four 3400 mt WW and four 1600 mt WW capacity barges. The overall daily disposal operation would last from 8 to 12 hours. For the worst-case disposal rate (SS) of 1650 mt DW/day, eight 3400 mt WW and eight 1600 mt WW capacity barges would be utilized. The overall daily disposal operation would last from 8 to 12 hours. For both disposal rate scenarios, there would be a 12 to 16 hour period at night in which no sludge would be dumped. It is assumed that under the above described disposal operation, sludge dumping would occur every day of the year.

The assumed disposal practice at the model site representative of the worst case is as stated for the typical site, except that barges would dump half their load along a track, then turn around and dispose of the balance along the same track in order to prevent a barge from dumping outside of the site. This practice would effectively halve the path length compared to the typical site.

b. Sludge concentration of pollutant (SC)

Typical	3.709 mg/kg DW
Worst	20.69 mg/kg DW

See Section 3, p. 3-4.

c. Disposal site characteristics

	Depth to pycnocline (D)	Average current velocity at site (V)
Typical	20 m	9500 m/day
Worst	5 m	4320 m/day

Typical site values are representative of a large, deep-water site with an area of about 1500 km^2 located beyond the continental shelf in the New York Bight. The pycnocline value of 20 m chosen is the average of the 10 to 30 m pycnocline depth range occurring in the summer and fall; the winter and spring disappearance of the pycnocline is not considered and so represents a conservative approach in evaluating annual or long-term impact. The current velocity of 11 cm/sec (9500 m/day) chosen is based on the average current velocity in this area (CDM, 1984b).

Worst-case values are representative of a near-shore New York Bight site with an area of about 20 km^2. The pycnocline value of 5 m chosen is the minimum value of the 5 to 23 m depth range of the surface mixed layer and is therefore a worst-case value. Current velocities in this area vary from 0 to 30 cm/sec. A value of 5 cm/sec (4320 m/day) is arbitrarily chosen to represent a worst-case value (CDM, 1984c).

4. Factors Considered in Initial Mixing

When a load of sludge is dumped from a moving tanker, an immediate mixing occurs in the turbulent wake of the vessel, followed by more gradual spreading of the plume. The entire plume, which initially constitutes a narrow band the length of the tanker path, moves more-or-less as a unit with the prevailing surface current and, under calm conditions, is not further dispersed by the current itself. However, the current acts to separate successive tanker loads, moving each out of the immediate disposal path before the next load is dumped.

Immediate mixing volume after barge disposal is approximately equal to the length of the dumping track with a cross-sectional area about four times that defined by the draft and width of the discharging vessel (Csanady, 1981, as cited in NOAA, 1983). The resulting plume is initially 10 m deep by 40 m wide (O'Connor and Park, 1982, as cited in NOAA, 1983). Subsequent spreading of plume band width occurs at an average rate of approximately 1 cm/sec (Csanady et al., 1979, as cited in NOAA, 1983). Vertical mixing is limited by the depth of the pycnocline or ocean floor, whichever is shallower. Four hours after disposal, therefore, average plume width (W) may be computed as follows:

$$W = 40\ m + 1\ cm/sec \times 4\ hours \times 3600\ sec/hour \times 0.01\ m/cm = 184\ m = \text{approximately } 200\ m$$

Thus the volume of initial mixing is defined by the tanker path, a 200 m width, and a depth appropriate to the site. For the typical (deep water) site, this depth is chosen as the pycnocline value of 20 m. For the worst (shallow water) site, a value of 10 m was chosen. At times the pycnocline may be as shallow as 5 m, but since the barge wake causes initial mixing to at least 10 m, the greater value was used.

5. **Index 1 Values (µg/L)**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	0.0	0.0074	0.0074
	Worst	0.0	0.041	0.041
Worst	Typical	0.0	0.063	0.063
	Worst	0.0	0.35	0.35

6. **Value Interpretation** - Value equals the expected increase in PA concentration in seawater around a disposal site as a result of sludge disposal after initial mixing.

7. **Preliminary Conclusion** - Slight increases in seawater concentration of PA occur when sludges are disposed at the typical site, but greater increases occur when sludges are dumped at the worst site.

B. **Index of Seawater Concentration Representing a 24-Hour Dumping Cycle (Index 2)**

1. **Explanation** - Calculates increased effective concentrations in µg/L of pollutant in seawater around an ocean disposal site utilizing a time weighted average (TWA) concentration. The TWA concentration is that which would be experienced by an organism remaining stationary (with respect to the ocean floor) or moving randomly within the disposal vicinity. The dilution volume is determined by the tanker path length and depth to pycnocline or, for the shallow water site, the 10 m effective mixing depth, as before, but the effective width is now determined by current movement perpendicular to the tanker path over 24 hours.

2. **Assumptions/Limitations** - Incorporates all of the assumptions used to calculate Index 1. In addition, it is assumed that organisms would experience high-pulsed sludge concentrations for 8 to 12 hours per day and then experience recovery (no exposure to sludge) for 12 to 16

hours per day. This situation can be expressed by the use of a TWA concentration of sludge constituent.

3. **Data Used and Rationale**

See Section 3, pp. 3-14 to 3-16.

4. **Factors Considered in Determining Subsequent Additional Degree of Mixing (Determination of TWA Concentrations)**

See Section 3, p. 3-17.

5. **Index 2 Values (µg/L)**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	0.0	0.0020	0.0040
	Worst	0.0	0.011	0.022
Worst	Typical	0.0	0.018	0.035
	Worst	0.0	0.099	0.20

6. **Value Interpretation** - Value equals the effective increase in PA concentration expressed as a TWA concentration in seawater around a disposal site experienced by an organism over a 24-hour period.

7. **Preliminary Conclusion** - After a 24-hour dumping cycle, increases occur in the seawater concentration of PA for all scenarios evaluated.

C. **Index of Toxicity to Aquatic Life (Index 3)**

1. **Explanation** - Compares the effective increased concentration of pollutant in seawater around the disposal site resulting from the initial mixing of sludge (Index 1) with the marine ambient water quality criterion of the pollutant, or with another value judged protective of marine aquatic life. For PA, this value is the criterion that will protect marine aquatic organisms from both acute and chronic toxic effects.

   Wherever a short-term, "pulse" exposure may occur as it would from initial mixing, it is usually evaluated using the "maximum" criteria values of EPA's ambient water quality criteria methodology. However, under this scenario, because the pulse is repeated several times daily on a long-term basis, potentially resulting in an accumulation of injury, it seems more appropriate to use

values designed to be protective against chronic toxicity. Therefore, to evaluate the potential for adverse effects on marine life resulting from initial mixing concentrations, as quantified by Index 1, the chronically derived criteria values are used.

2. **Assumptions/Limitations** - In addition to the assumptions stated for Indices 1 and 2, assumes that all of the released pollutant is available in the water column to move through predicted pathways (i.e., sludge to seawater to aquatic organism to man). The possibility of effects arising from accumulation in the sediments is neglected since the U.S. EPA presently lacks a satisfactory method for deriving sediment criteria.

3. **Data Used and Rationale**

   a. **Concentration of pollutant in seawater around a disposal site (Index 1)**

      See Section 3, p. 3-17.

   b. **Ambient water quality criterion (AWQC)** = 300 µg/L

      Water quality criteria for the toxic pollutants listed under Section 307(a)(1) of the Clean Water Act of 1977 were developed by the U.S. EPA under Section 304(a)(1) of the Act. These criteria were derived by utilization of data reflecting the resultant environmental impacts and human health effects of these pollutants if present in any body of water. The criteria values presented in this assessment are excerpted from the ambient water quality criteria document for PAHs.

      No PA-specific criteria values are immediately available. The 300 µg/L value chosen as the criterion to protect saltwater organisms is an acute toxicity value based on tests of polychaete worms exposed to crude oil fractions. No data are presently available regarding the chronic effects of PAHs on more sensitive marine aquatic life (U.S. EPA, 1980).

4. **Index 3 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	0.0	0.000025	0.000025
	Worst	0.0	0.00014	0.00014
Worst	Typical	0.0	0.00021	0.00021
	Worst	0.0	0.0012	0.0012

5. **Value Interpretation** - Value equals the factor by which the expected seawater concentration increase in PA exceeds the protective value. A value > 1 indicates that acute or chronic toxic conditions may exist for organisms at the site.

6. **Preliminary Conclusion** - Only slight increases of incremental hazard to aquatic life occur for all of the scenarios evaluated.

D. **Index of Human Cancer Risk Resulting from Seafood Consumption (Index 4)**

1. **Explanation** - Estimates the expected increase in human pollutant intake associated with the consumption of seafood, a fraction of which originates from the disposal site vicinity, and compares the total expected pollutant intake with the cancer risk-specific intake (RSI) of the pollutant.

2. **Assumptions/Limitations** - In addition to the assumptions listed for Indices 1 and 2, assumes that the seafood tissue concentration increase can be estimated from the increased water concentration by a bioconcentration factor. It also assumes that, over the long term, the seafood catch from the disposal site vicinity will be diluted to some extent by the catch from uncontaminated areas.

3. **Data Used and Rationale**

a. **Concentration of pollutant in seawater around a disposal site (Index 2)**

See Section 3, p. 3-18.

Since bioconcentration is a dynamic and reversible process, it is expected that uptake of sludge pollutants by marine organisms at the disposal site

will reflect TWA concentrations, as quantified by Index 2, rather than pulse concentrations.

b. Dietary consumption of seafood (QF)

Typical	14.3 g WW/day
Worst	41.7 g WW/day

Typical and worst-case values are the mean and the 95th percentile, respectively, for all seafood consumption in the United States (Stanford Research Institute (SRI) International, 1980).

c. Fraction of consumed seafood originating from the disposal site (FS)

For a typical harvesting scenario, it was assumed that the total catch over a wide region is mixed by harvesting, marketing and consumption practices, and that exposure is thereby diluted. Coastal areas have been divided by the National Marine Fishery Service (NMFS) into reporting areas for reporting on data on seafood landings. Therefore it was convenient to express the total area affected by sludge disposal as a fraction of an NMFS reporting area. The area used to represent the disposal impact area should be an approximation of the total ocean area over which the average concentration defined by Index 2 is roughly applicable. The average rate of plume spreading of 1 cm/sec referred to earlier amounts to approximately 0.9 km/day. Therefore, the combined plume of all sludge dumped during one working day will gradually spread, both parallel to and perpendicular to current direction, as it proceeds down-current. Since the concentration has been averaged over the direction of current flow, spreading in this dimension will not further reduce average concentration; only spreading in the perpendicular dimension will reduce the average. If stable conditions are assumed over a period of days, at least 9 days would be required to reduce the average concentration by one-half. At that time, the original plume length of approximately 8 km (8000 m) will have doubled to approximately 16 km due to spreading.

It is probably unnecessary to follow the plume further since storms, which would result in much more rapid dispersion of pollutants to background concentrations are expected on at least a 10-day frequency (NOAA, 1983). Therefore, the area impacted by sludge disposal (AI, in km^2) at each disposal site will be considered to be defined by the tanker path length (L) times the distance of

current movement (V) during 10 days, and is computed as follows:

$$AI = 10 \times L \times V \times 10^{-6}\ km^2/m^2 \qquad (1)$$

To be consistent with a conservative approach, plume dilution due to spreading in the perpendicular direction to current flow is disregarded. More likely, organisms exposed to the plume in the area defined by equation 1 would experience a TWA concentration lower than the concentration expressed by Index 2.

Next, the value of AI must be expressed as a fraction of an NMFS reporting area. In the New York Bight, which includes NMFS areas 612-616 and 621-623, deep-water area 623 has an area of approximately 7200 km^2 and constitutes approximately 0.02 percent of the total seafood landings for the Bight (CDM, 1984b). Near-shore area 612 has an area of approximately 4300 km^2 and constitutes approximately 24 percent of the total seafood landings (CDM, 1984c). Therefore the fraction of all seafood landings (FS_t) from the Bight which could originate from the area of impact of either the typical (deep-water) or worst (near-shore) site can be calculated for this typical harvesting scenario as follows:

For the typical (deep water) site:

$$FS_t = \frac{AI \times 0.02\%}{7200\ km^2} = \qquad (2)$$

$$\frac{[10 \times 8000\ m \times 9500\ m \times 10^{-6}\ km^2/m^2] \times 0.0002}{7200\ km^2} = 2.1 \times 10^{-5}$$

For the worst (near shore) site:

$$FS_t = \frac{AI \times 24\%}{4300\ km^2} = \qquad (3)$$

$$\frac{[10 \times 4000\ m \times 4320\ m \times 10^{-6}\ km^2/m^2] \times 0.24}{4300\ km^2} = 9.6 \times 10^{-3}$$

To construct a worst-case harvesting scenario, it was assumed that the total seafood consumption for an individual could originate from an area more limited than the entire New York Bight. For example, a particular fisherman providing the entire seafood diet for himself or others could fish habitually within a single NMFS reporting area. Or, an individual could have a preference for a particular species which is taken only over a more

limited area, here assumed arbitrarily to equal an NMFS reporting area. The fraction of consumed seafood (FS_w) that could originate from the area of impact under this worst-case scenario is calculated as follows:

For the typical (deep water) site:

$$FS_w = \frac{AI}{7200\ km^2} = 0.11 \qquad (4)$$

For the worst (near shore) site:

$$FS_w = \frac{AI}{4300\ km^2} = 0.040 \qquad (5)$$

d. **Bioconcentration factor of pollutant (BCF) =** 486 L/kg

The value chosen is the weighted average BCF of PA for the edible portion of all freshwater and estuarine aquatic organisms consumed by U.S. citizens (U.S. EPA, 1980). The weighted average BCF is derived as part of the water quality criteria developed by the U.S. EPA to protect human health from the potential carcinogenic effects of PA induced by ingestion of contaminated water and aquatic organisms. Although no measured steady-state BCF for PA is available, a BCF value for aquatic organisms containing about 7.6 percent lipids can be estimated from the octanol-water partition coefficient. The weighted average BCF is derived by applying an adjustment factor to the BCF estimate to correct for the 3 percent lipid content of consumed fish and shellfish. It should be noted, however, that the resulting estimated weighted average BCF of 486 L/kg represents a worst-case situation. Although data concerning the environmental impacts of PAHs are incomplete, the results of numerous studies show that PAHs demonstrate little tendency for bioaccumulation due to their rapid metabolism. A BCF of 30 obtained from a study of mosquitofish may represent a more realistic value (U.S. EPA, 1980). It should be noted that lipids of marine species differ in both structure and quantity from those of freshwater species. Although a BCF value calculated entirely from marine data would be more appropriate for this assessment, no such data are presently available.

e. **Average daily human dietary intake of pollutant (DI)** - Data not immediately available.

f. **Cancer potency** - Data not immediately available.

g. **Cancer risk-specific intake (RSI)** - Data not immediately available.

4. **Index 4 Values** - Values were not calculated due to lack of data.

5. **Value Interpretation** - Value equals factor by which the expected intake exceeds the RSI. A value >1 indicates a possible human health threat. Comparison with the null index value at 0 mt/day indicates the degree to which any hazard is due to sludge disposal, as opposed to preexisting dietary sources.

6. **Preliminary Conclusion** - Conclusion was not drawn because index values could not be calculated.

SECTION 4

PRELIMINARY DATA PROFILE FOR PHENANTHRENE IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

Detected in 53% of 437 samples from 40 POTWs	U.S. EPA, 1982 (p. 41)
Detected in 43% of 42 samples from 10 POTWs	U.S. EPA, 1982 (p. 49)
Detected in sludges of 12 and 13 POTWs	Naylor and Loehr, 1982 (p. 20)

2. Concentration

1 to 10,100 µg/L range for 232 samples from 40 POTWs	U.S. EPA, 1982 (p. 41)
27 to 35,000 µg/L range for 18 samples from 10 POTWs	U.S. EPA, 1982 (p. 49)
7.4 µg/g (DW) median, 0.89 to 44 µg/g range for 12 POTWs	Naylor and Loehr, 1982 (p. 20)
278 µg/L median, 34 to 1,565 range for 12 POTWs	

Percent occurrence of PA at indicated concentrations in 25 U.S. cities (DW) — U.S. EPA, 1983b (p. A-13)

>1 µg/g	>10 µg/g	>50 µg/g
60	20	8

Dry-weight concentration of PA in sludge — Statistically derived from data presented in a survey of POTWs throughout the United States (U.S. EPA, 1982)

POTWs analyzed	39
Minimum concentration	0.201 µg/g DW
Maximum concentration	30.128 µg/g DW
Average concentration	5.98 µg/g DW
50th percentile	3.709 µg/g DW
95th percentile	20.69 µg/g DW

B. **Soil - Unpolluted**

Data not immediately available.

Soil half-lives of PAHs may range from <1 day to several years depending on a variety of factors including volatility, photoliability, and microbial degradation. — U.S. EPA, 1984a (p. 1-4)

C. **Water - Unpolluted**

1. **Frequency of Detection**

Data not immediately available.

2. **Concentration**

River water: 1280 ± 320 ng/L — Ogan et al., 1979 (p. 1318)

D. **Air**

1. **Frequency of Detection**

Data not immediately available.

2. **Concentration**

Range in U.S. cities in "recent" years: 0.011 to 0.340 ng/m^3 — U.S. EPA, 1980 (p. C-35)

E. **Food**

1. **Total Average Intake**

Data not immediately available.

2. **Concentration**

Coconut oil - 51 μg/L
Charcoal broiled steaks - 0.21 μg/g
Barbequed ribs - 0.58 μg/g
Smoked mutton - 0.104 μg/g
Smoked mutton sausages - 0.017 μg/g

U.S. EPA, 1980 (p. C-13)

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity

a. Qualitative Assessment

There is no evidence of the carcinogenicity of PA to humans exposed by the oral or inhalation routes, and this compound has not been tested for carcinogenicity in experimental animals by oral or inhalation exposure. Administration of PA in three intraperitoneal injections on days 1, 8, and 15 of life at levels of 0.2, 0.4, and 0.8 μmol did not result in an increased incidence of tumors in 100 Swiss-Webster mice (Buening et al., 1979). IARC (1983) reported that there was insufficient evidence of carcinogenic risk to humans and experimental animals associated with oral or inhalation exposure to PA. Using the IARC criteria for evaluating the overall weight of evidence of carcinogenicity to humans, PA is most appropriately classified as a Group 3 chemical, i.e., "cannot be classified as to its carcinogenic potential for humans."

U.S. EPA, 1984b (p. 5, 6)

b. Potency

Not derived due to lack of evidence.

2. Chronic Toxicity

a. ADI

Data not immediately available.

b. Effects

PAHs have been demonstrated to decrease body growth in rats and mice. Damage to hemopoetic and lymphatic tissue is common.

U.S. EPA, 1980 (p. C-51)

3. **Absorption Factor**

PAHs have been shown to cross intestinal tissues.	U.S. EPA, 1980 (p. C-37)

4. **Existing Regulations**

1970 drinking water standard set by the World Health Organization recommends that PAH concentration not exceed 0.2 µg/L.	U.S. EPA, 1980 (p. C-108)

B. **Inhalation**

1. **Carcinogenicity**

a. **Qualitative Assessment**

IARC Group 3: "cannot be classified to its carcinogenic potential for humans."	U.S. EPA, 1984b (p. 6)

b. **Potency**

Not derived due to lack of evidence.

2. **Chronic Toxicity**

Data not immediately available concerning non-tumor related chronic toxicity of PAHs due to inhalation.	U.S. EPA, 1984a (p. 8)

3. **Absorption Factor**

Data not immediately available.

4. **Existing Regulations**

Regulations concerning exposure to individual PAHs do not exist. However, a number of standards concerning work-place exposure limits for benzene-cyclohexane extractable mixtures of PAHs have been recommended by various U.S. agencies.	U.S. EPA, 1980 (p. C-108)

III. PLANT EFFECTS

Data not immediately available.

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

Redwinged blackbird: LD_{50} = 113 mg/kg	Schafer et al., 1983 (p. 360)

B. Uptake

In a laboratory microcosm study with 135 mg/cm^3 of PA being applied to wood posts resulting in soil concentration of <0.02 to 0.73 µg/g PA, a vole placed in a microcosm accumulated 7.20 µg PA in its whole body. This resulted in a biomagnification from soil of 9.86.	Gile et al., 1982 (p. 297-299)

V. AQUATIC LIFE EFFECTS

A. Toxicity

1. Freshwater

Data not immediately available.

2. Saltwater

Acute toxicity value of 300 µg/L is based on tests of polychaete worms exposed to crude oil fractions.	U.S. EPA, 1980 (p. B-1, 2)

B. Uptake

The estimated weighted average BCF of PA for the edible portion of all freshwater and estuarine aquatic organisms consumed by U.S. citizens is 486.	U.S. EPA, 1980 (p. C-17)

VI. SOIL BIOTA EFFECTS

See Table 4-1.

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Water solubility at 25°C: 1.29 mg/L Henry's Law constant (H): 3.93×10^{-5}	Mackay et al., 1979 (p. 336)
Molecular weight: 178.23 Melting point: 101°C Vapor pressure: 6.8×10^{-4} torr	U.S. EPA, 1980 (p. A-3)
K_{oc} for PA has been estimated to be 23,000 based on octanol:water partition coefficient data.	Hassett et al., 1983

TABLE 4-1. UPTAKE OF PHENANTHRENE BY SOIL BIOTA

Species	Chemical Form Applied	Soil Type	Range of Soil Concentration (μg/g DW)	Range of Tissue Concentration (μg/g DW)	Bioconcentration Factor[a]	References
Cricket	PA in wood post at 135 mg/cm^3	lab	<0.02-0.73	<0.25-1.22	<1-1.67	Gile et al., 1982 (p. 298)
Snail	PA in wood post at 135 mg/cm^3	lab	<0.02-0.73	<0.25-5.65	<1-7.74	Gile et al., 1982 (p. 298)
Pill bug	PA in wood post at 135 mg/m^3	lab	<0.02-0.73	<0.25-1.72	<1-2.36	Gile et al., 1982 (p. 298)
Tenebrio	PA in wood post at 135 mg/cm^3	lab	<0.02-0.73	<0.25	<1	Gile et al., 1982 (p. 298)
Worm	PA in wood post at 135 mg/cm^3	lab	<0.02-0.73	<0.25-8.13	25.07	Gile et al., 1982 (p. 298)

[a] BF = Tissue concentration/soil concentration.

SECTION 5

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APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR PHENANTHRENE IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

Based on the recommendations of the experts at the OWRS meetings (April-May, 1984), an assessment of this reuse/disposal option is not being conducted at this time. The U.S. EPA reserves the right to conduct such an assessment for this option in the future.

II. LANDFILLING

A. Procedure

Using Equation 1, several values of C/C_o for the unsaturated zone are calculated corresponding to increasing values of t until equilibrium is reached. Assuming a 5-year pulse input from the landfill, Equation 3 is employed to estimate the concentration vs. time data at the water table. The concentration vs. time curve is then transformed into a square pulse having a constant concentration equal to the peak concentration, C_u, from the unsaturated zone, and a duration, t_o, chosen so that the total areas under the curve and the pulse are equal, as illustrated in Equation 3. This square pulse is then used as the input to the linkage assessment, Equation 2, which estimates initial dilution in the aquifer to give the initial concentration, C_o, for the saturated zone assessment. (Conditions for B, minimum thickness of unsaturated zone, have been set such that dilution is actually negligible.) The saturated zone assessment procedure is nearly identical to that for the unsaturated zone except for the definition of certain parameters and choice of parameter values. The maximum concentration at the well, C_{max}, is used to calculate the index values given in Equations 4 and 5.

B. Equation 1: Transport Assessment

$$\frac{C(\chi,t)}{C_o} = \frac{1}{2}\,[\exp(A_1)\ \mathrm{erfc}(A_2) + \exp(B_1)\ \mathrm{erfc}(B_2)] = P(\chi,t)$$

Requires evaluations of four dimensionless input values and subsequent evaluation of the result. $\mathrm{Exp}(A_1)$ denotes the exponential of A_1, e^{A_1}, where $\mathrm{erfc}(A_2)$ denotes the complimentary error function of A_2. $\mathrm{Erfc}(A_2)$ produces values between 0.0 and 2.0 (Abramowitz and Stegun, 1972).

where:

$$A_1 = \frac{\chi}{2D^*} [V^* - (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}]$$

$$A_2 = \frac{\chi - t\ (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}}{(4D^* \times t)^{\frac{1}{2}}}$$

$$B_1 = \frac{\chi}{2D^*} [V^* + (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}]$$

$$B_2 = \frac{\chi + t\ (V^{*2} + 4D^* \times \mu^*)^{\frac{1}{2}}}{(4D^* \times t)^{\frac{1}{2}}}$$

and where for the unsaturated zone:

C_o = SC x CF = Initial leachate concentration (μg/L)
SC = Sludge concentration of pollutant (mg/kg DW)
CF = 250 kg sludge solids/m^3 leachate =

$$\frac{PS \times 10^3}{1 - PS}$$

PS = Percent solids (by weight) of landfilled sludge = 20%
t = Time (years)
χ = h = Depth to groundwater (m)
D^* = $\alpha \times V^*$ (m^2/year)
α = Dispersivity coefficient (m)

$$V^* = \frac{Q}{\Theta \times R} \text{ (m/year)}$$

Q = Leachate generation rate (m/year)
Θ = Volumetric water content (unitless)

$$R = 1 + \frac{P_{dry}}{\Theta} \times K_d = \text{Retardation factor (unitless)}$$

P_{dry} = Dry bulk density (g/mL)
K_d = $f_{oc} \times K_{oc}$ (mL/g)
f_{oc} = Fraction of organic carbon (unitless)
K_{oc} = Organic carbon partition coefficient (mL/g)

$$\mu^* = \frac{365 \times \mu}{R} \text{ (years)}^{-1}$$

μ = Degradation rate (day^{-1})

and where for the saturated zone:

C_o = Initial concentration of pollutant in aquifer as determined by Equation 2 (μg/L)
t = Time (years)
χ = $\Delta\ell$ = Distance from well to landfill (m)
D^* = $\alpha \times V^*$ (m^2/year)
α = Dispersivity coefficient (m)

$$V^* = \frac{K \times i}{\emptyset \times R} \text{ (m/year)}$$

K = Hydraulic conductivity of the aquifer (m/day)
i = Average hydraulic gradient between landfill and well (unitless)
$\emptyset$ = Aquifer porosity (unitless)

$$R = 1 + \frac{P_{dry}}{\emptyset} \times K_d = \text{Retardation factor} = 1 \text{ (unitless)}$$

since $K_d = f_{oc} \times K_{oc}$ and f_{oc} is assumed to be zero for the saturated zone.

C. Equation 2. Linkage Assessment

$$C_o = C_u \times \frac{Q \times W}{365 \cdot [(K \times i) \div \emptyset] \times B}$$

where:

C_o = Initial concentration of pollutant in the saturated zone as determined by Equation 1 (µg/L)
C_u = Maximum pulse concentration from the unsaturated zone (µg/L)
Q = Leachate generation rate (m/year)
W = Width of landfill (m)
K = Hydraulic conductivity of the aquifer (m/day)
i = Average hydraulic gradient between landfill and well (unitless)
$\emptyset$ = Aquifer porosity (unitless)
B = Thickness of saturated zone (m) where:

$$B \geq \frac{Q \times W \times \emptyset}{K \times i \times 365} \text{ and } B \geq 2$$

D. Equation 3. Pulse Assessment

$$\frac{C(\chi,t)}{C_o} = P(\chi,t) \text{ for } 0 \leq t \leq t_o$$

$$\frac{C(\chi,t)}{C_o} = P(\chi,t) - P(\chi,t - t_o) \text{ for } t > t_o$$

where:

t_o (for unsaturated zone) = LT = Landfill leaching time (years)

t_o (for saturated zone) = Pulse duration at the water table (χ = h) as determined by the following equation:

$$t_o = [\int_o^\infty C\, dt] \div C_u$$

$$P(\chi,t) = \frac{C(\chi,t)}{C_o} \text{ as determined by Equation 1}$$

E. **Equation 4. Index of Groundwater Concentration Resulting from Landfilled Sludge (Index 1)**

1. **Formula**

Index 1 = C_{max}

where:

C_{max} = Maximum concentration of pollutant at well = maximum of $C(\Delta\ell,t)$ calculated in Equation 1 (µg/L)

2. **Sample Calculation**

0.101 µg/L = 0.101 µg/L.

F. **Equation 5. Index of Human Cancer Risk Resulting from Groundwater Contamination (Index 2)**

1. **Formula**

$$\text{Index 2} = \frac{(I_1 \times AC) + DI}{RSI}$$

where:

I_1 = Index 1 = Index of groundwater concentration resulting from landfilled sludge (µg/L)
AC = Average human consumption of drinking water (L/day)
DI = Average daily human dietary intake of pollutant (µg/day)
RSI = Cancer risk-specific intake (µg/day)

2. **Sample Calculation** - Values were not calculated due to lack of data.

III. INCINERATION

A. **Index of Air Concentration Increment Resulting from Incinerator Emissions (Index 1)**

1. **Formula**

$$\text{Index 1} = \frac{(C \times DS \times SC \times FM \times DP) + BA}{BA}$$

where:

C = Coefficient to correct for mass and time units (hr/sec x g/mg)
DS = Sludge feed rate (kg/hr DW)

SC = Sludge concentration of pollutant (mg/kg DW)
FM = Fraction of pollutant emitted through stack (unitless)
DP = Dispersion parameter for estimating maximum annual ground level concentration ($\mu g/m^3$)
BA = Background concentration of pollutant in urban air ($\mu g/m^3$)

2. Sample Calculation

$$8.64 = [(2.78 \times 10^{-7} \text{ hr/sec} \times \text{g/mg} \times 2660 \text{ kg/hr DW} \times 3.709 \text{ mg/kg DW} \times 0.05 \times 3.4\ \mu g/m^3) + 0.000061\ \mu g/m^3] \div 0.000061\ \mu g/m^3$$

B. Index of Human Cancer Risk Resulting from Inhalation of Incinerator Emissions (Index 2)

1. Formula

$$\text{Index 2} = \frac{[(I_1 - 1) \times BA] + BA}{EC}$$

where:

I_1 = Index 1 = Index of air concentration increment resulting from incinerator emissions (unitless)
BA = Background concentration of pollutant in urban air ($\mu g/m^3$)
EC = Exposure criterion ($\mu g/m^3$)

2. Sample Calculation - Values were not calculated due to lack of data.

IV. OCEAN DISPOSAL

A. Index of Seawater Concentration Resulting from Initial Mixing of Sludge (Index 1)

1. Formula

$$\text{Index 1} = \frac{SC \times ST \times PS}{W \times D \times L}$$

where:

SC = Sludge concentration of pollutant (mg/kg DW)
ST = Sludge mass dumped by a single tanker (kg WW)
PS = Percent solids in sludge (kg DW/kg WW)

W = Width of initial plume dilution (m)
D = Depth to pycnocline or effective depth of mixing for shallow water site (m)
L = Length of tanker path (m)

2. **Sample Calculation**

$$0.0074\ \mu g/L = \frac{3.709\ mg/kg\ DW \times 1600000\ kg\ WW \times 0.04\ kg\ DW/kg\ WW \times 10^3 \mu g/mg}{200\ m \times 20\ m \times 8000\ m \times 10^3\ L/m^3}$$

B. **Index of Seawater Concentration Representing a 24-Hour Dumping Cycle (Index 2)**

1. **Formula**

$$\text{Index 2} = \frac{SS \times SC}{V \times D \times L}$$

where:

SS = Daily sludge disposal rate (kg DW/day)
SC = Sludge concentration of pollutant (mg/kg DW)
V = Average current velocity at site (m/day)
D = Depth to pycnocline or effective depth of mixing for shallow water site (m)
L = Length of tanker path (m)

2. **Sample Calculation**

$$0.0020\ \mu g/L = \frac{825000\ kg\ DW/day \times 3.709\ mg/kg\ DW \times 10^3\ \mu g/mg}{9500\ m/day \times 20\ m \times 8000\ m \times 10^3\ L/m^3}$$

C. **Index of Toxicity to Aquatic Life (Index 3)**

1. **Formula**

$$\text{Index 3} = \frac{I_1}{AWQC}$$

where:

I_1 = Index 1 = Index of seawater concentration resulting from initial mixing after sludge disposal (µg/L)
AWQC = Criterion or other value expressed as an average concentration to protect marine organisms from acute and chronic toxic effects (µg/L)

2. **Sample Calculation**

$$0.000025 = \frac{0.0074\ \mu g/L}{300\ \mu g/L}$$

D. **Index of Human Cancer Risk Resulting from Seafood Consumption (Index 4)**

1. **Formula**

$$\text{Index 4} = \frac{(I_2 \times BCF \times 10^{-3}\ kg/g \times FS \times QF) + DI}{RSI}$$

where:

I_2 = Index 2 = Index of seawater concentration representing a 24-hour dumping cycle (µg/L)
QF = Dietary consumption of seafood (g WW/day)
FS = Fraction of consumed seafood originating from the disposal site (unitless)
BCF = Bioconcentration factor of pollutant (L/kg)
DI = Average daily human dietary intake of pollutant (µg/day)
RSI = Cancer risk-specific intake (µg/day)

2. **Sample Calculation** - Values were not calculated due to lack of data.

TABLE A-1. INPUT DATA VARYING IN LANDFILL ANALYSIS AND RESULT FOR EACH CONDITION

Input Data	Condition of Analysis							
	1	2	3	4	5	6	7	8
Sludge concentration of pollutant, SC (μg/g DW)	3.709	20.69	3.709	3.709	3.709	3.709	20.69	N[a]
Unsaturated zone								
Soil type and characteristics								
Dry bulk density, P_{dry} (g/mL)	1.53	1.53	1.925	NA[b]	1.53	1.53	NA	N
Volumetric water content, θ (unitless)	0.195	0.195	0.133	NA	0.195	0.195	NA	N
Fraction of organic carbon, f_{oc} (unitless)	0.005	0.005	0.0001	NA	0.005	0.005	NA	N
Site parameters								
Leachate generation rate, Q (m/year)	0.8	0.8	0.8	1.6	0.8	0.8	1.6	N
Depth to groundwater, h (m)	5	5	5	0	5	5	0	N
Dispersivity coefficient, α (m)	0.5	0.5	0.5	NA	0.5	0.5	NA	N
Saturated zone								
Soil type and characteristics								
Aquifer porosity, ϕ (unitless)	0.44	0.44	0.44	0.44	0.389	0.44	0.389	N
Hydraulic conductivity of the aquifer, K (m/day)	0.86	0.86	0.86	0.86	4.04	0.86	4.04	N
Site parameters								
Hydraulic gradient, i (unitless)	0.001	0.001	0.001	0.001	0.001	0.02	0.02	N
Distance from well to landfill, Δℓ (m)	100	100	100	100	100	50	50	N
Dispersivity coefficient, α (m)	10	10	10	10	10	5	5	N

TABLE A-1. (continued)

Results	Condition of Analysis							
	1	2	3	4	5	6	7	8
Unsaturated zone assessment (Equations 1 and 3)								
Initial leachate concentration, C_o (μg/L)	927	5170	927	927	927	927	5170	N
Peak concentration, C_u (μg/L)	4.69	26.1	178	927	4.69	4.69	5170	N
Pulse duration, t_o (years)	989	989	26.0	5.00	989	989	5.00	N
Linkage assessment (Equation 2)								
Aquifer thickness, B (m)	126	126	126	253	23.8	6.32	2.38	N
Initial concentration in saturated zone, C_o (μg/L)	4.69	26.1	178	927	4.69	4.69	5170	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (μg/L)	0.101	0.563	0.101	0.101	0.532	3.29	120.0	N
Index of groundwater concentration resulting from landfilled sludge, Index 1 (μg/L) (Equation 4)	0.101	0.563	0.101	0.101	0.532	3.29	120.0	0
Index of human cancer risk resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	NC[c]	NC	NC	NC	NC	NC	NC	NC

[a]N = Null condition, where no landfill exists; no value is used.
[b]NA = Not applicable for this condition.
[c]NC = Not calculated due to lack of data.