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Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Benzo(a)pyrene

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. Benzo(a)pyrene (BaP) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing), placed in a landfill, incinerated or ocean disposed.* This profile is a compilation of information that may be useful in determining whether BaP 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 → soil → plant uptake → animal uptake → 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 landspreading and distribution and marketing, 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 BENZO(A)PYRENE 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

A. Effect on Soil Concentration of Benzo(a)pyrene

Landspreading of sludge may slightly increase the soil concentration of BaP when sludge containing a high concentration of BaP is applied at the 50 and 500 mt/ha rates (see Index 1).

B. Effect on Soil Biota and Predators of Soil Biota

Conclusions were not drawn because index values could not be calculated due to lack of data.

C. Effect on Plants and Plant Tissue Concentration

The potential toxicity of increased soil concentrations of BaP to plants could not be determined due to lack of data (see Index 4).

Landspreading of sludge containing a high concentration of BaP is expected to slightly increase the tissue concentration of BaP in plants in the animal and human diet (see Index 5).

The maximum plant tissue concentration which is permitted by phytotoxicity could not be determined due to lack of data (see Index 6).

D. Effect on Herbivorous Animals

The concentration of BaP in plants grown on sludge-amended soil is not expected to exceed the dietary concentration which is toxic to herbivorous animals (see Index 7).

Landspreading of sludge is not expected to pose a toxic hazard due to BaP for grazing animals that incidentally ingest sludge-amended soil (see Index 8).

E. Effect on Humans

For toddlers who consume plants grown in sludge-amended soil, an increase in the risk of cancer due to BaP is expected when sludges containing the worst-case concentration of BaP are landspread. For adults, an increase in the risk of cancer is expected when sludges containing a typical concentration of BaP are applied at the rates of 50 and 500 mt/ha, and when sludges containing a worst-case concentration are applied at any rate (5 to 500 mt/ha) (see Index 9).

A conclusion was not drawn as to the cancer risk resulting from consumption of animal products derived from animals feeding on plants because the index values could not be calculated due to lack of data (see Index 10).

A conclusion was not drawn as to the cancer risk resulting from consumption of animal products derived from animals ingesting soil because the index values could not be calculated due to lack of data (see Index 11).

An increase in the risk of cancer is expected to occur for toddlers who ingest sludge-amended soil when sludges containing atypically high concentrations of BaP are applied to soil at high rates (50 and 500 mt/ha) (see Index 12).

The aggregate human cancer risk due to BaP resulting from landspreading of sludge could not be evaluated due to lack of data (see Index 13).

II. LANDFILLING

The concentration of BaP in groundwater at the well is expected to increase when sludge is disposed in landfills. The greatest increase in the groundwater concentration is expected when worst-case conditions exist in both the unsaturated and saturated zones (see Index 1).

The risk of cancer due to BaP in groundwater is expected to atypically increase above the pre-existing risk due to dietary sources only when sludges with atypically high concentrations of BaP are disposed in landfills which are characterized by the worst-case conditions (see Index 2).

III. INCINERATION

The concentration of BaP in air is expected to increase as the sludge feed rate and concentration of BaP in sludge increase. An exception is found when sludge containing a typical concentration of BaP is burned at a low rate (2660 kg/hr DW); in this case no increase is expected (see Index 1).

Incineration of sludge is expected to increase the cancer risk due to inhalation of BaP above the risk posed by background urban air concentrations of BaP. This increase may be substantial when sludge containing a high concentration of BaP is incinerated at a high feed rate and a large fraction of the pollutant is emitted through the stack (see Index 2).

IV. OCEAN DISPOSAL

Only slight increases of BaP occur after the dumping of sludges and initial mixing (see Index 1). Only slight increases of seawater BaP concentrations occur after a 24-hour dumping cycle (see Index 2). Only slight increases in the incremental hazard to aquatic life are evident for worst-concentration sludges dumped at the typical and worst sites. No increase is apparent for typical sludges dumped at typical sites (see Index 3). Increases in human health risk are apparent from consuming seafood taken from typical or worst sites after dumping of sludges containing worst concentrations of BaP (see Index 4).

SECTION 3

PRELIMINARY HAZARD INDICES FOR BENZO(A)PYRENE IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Benzo(a)pyrene

1. Index of Soil Concentration (Index 1)

a. **Explanation** - Calculates concentrations in μg/g DW of pollutant in sludge-amended soil. Calculated for sludges with typical (median, if available) and worst (95 percentile, if available) pollutant concentrations, respectively, for each of four applications. Loadings (as dry matter) are chosen and explained as follows:

0 mt/ha	No sludge applied. Shown for all indices for purposes of comparison, to distinguish hazard posed by sludge from pre-existing hazard posed by background levels or other sources of the pollutant.
5 mt/ha	Sustainable yearly agronomic application; i.e., loading typical of agricultural practice, supplying ~50 kg available nitrogen per hectare.
50 mt/ha	Higher single application as may be used on public lands, reclaimed areas or home gardens.
500 mt/ha	Cumulative loading after 100 years of application at 5 mt/ha/year.

b. **Assumptions/Limitations** - Assumes pollutant is incorporated into the upper 15 cm of soil (i.e., the plow layer), which has an approximate mass (dry matter) of 2 x 10^3 mt/ha and is then dissipated through first order processes which can be expressed as a soil half-life.

c. **Data Used and Rationale**

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

Typical	0.143 μg/g DW
Worst	1.937 μg/g DW

The typical and worst sludge concentrations are the median and 95th percentile values statistically derived from sludge concentration data from a survey of 40 publicly-owned treatment works (POTWs) (U.S. EPA, 1982). (See Section 4, p. 4-1.)

ii. **Background concentration of pollutant in soil (BS) = 0.1 μg/g DW**

In agricultural and forest conditions reasonably removed from industrial and urban influence, the levels of BaP are approximately 0 to 10 ppb (Kolan et al., 1975 and Hites et al., 1977 as cited by Overcash, 1984).

iii. **Soil half-life of pollutant ($t_{\frac{1}{2}}$) = 0.18986 years**

The value given was derived from a degradation rate of 0.01 day^{-1} (Herbes and Schwall, 1978). (See Section 4, p. 4-8.)

d. **Index 1 Values (μg/g DW)**

Sludge Concentration	Sludge Application Rate (mt/ha)			
	0	5	50	500
Typical	0.10	0.10	0.10	0.10
Worst	0.10	0.10	0.14	0.11

e. **Value Interpretation** - Value equals the expected concentration in sludge-amended soil.

f. **Preliminary Conclusion** - Landspreading of sludge may slightly increase the soil concentration of BaP when sludge containing a high concentration of BaP is applied at the 50 and 500 mt/ha rates.

B. **Effect on Soil Biota and Predators of Soil Biota**

1. **Index of Soil Biota Toxicity (Index 2)**

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with soil concentration shown to be toxic for some soil organism.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Soil concentration toxic to soil biota (TB)** - Data not immediately available.

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

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds toxic concentration. Value > 1 indicates a toxic hazard may exist for soil biota.

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

2. **Index of Soil Biota Predator Toxicity (Index 3)**

a. **Explanation** - Compares pollutant concentrations expected in tissues of organisms inhabiting sludge-amended soil with food concentration shown to be toxic to a predator on soil organisms.

b. **Assumptions/Limitations** - Assumes pollutant form bioconcentrated by soil biota is equivalent in toxicity to form used to demonstrate toxic effects in predator. Effect level in predator may be estimated from that in a different species.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Uptake factor of pollutant in soil biota (UB)** - Data not immediately available.

iii. **Feed concentration toxic to predator (TR)** - Data not immediately available.

d. **Index 3 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Values equals factor by which expected concentration in soil biota exceeds that which is toxic to predator. Value > 1 indicates a toxic hazard may exist for predators of soil biota.

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

C. Effect on Plants and Plant Tissue Concentration

1. Index of Phytotoxic Soil Concentration (Index 4)

a. **Explanation** - Compares pollutant concentrations in sludge-amended soil with the lowest soil concentration shown to be toxic for some plants.

b. **Assumptions/Limitations** - Assumes pollutant form in sludge-amended soil is equally bioavailable and toxic as form used in study where toxic effects were demonstrated.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Soil concentration toxic to plants (TP)** - Data not immediately available.

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

e. **Value Interpretation** - Value equals factor by which soil concentration exceeds phytotoxic concentration. Value > 1 indicates a phytotoxic hazard may exist.

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

2. Index of Plant Concentration Caused by Uptake (Index 5)

a. **Explanation** - Calculates expected tissue concentrations, in μg/g DW, in plants grown in sludge-amended soil, using uptake data for the most responsive plant species in the following categories: (1) plants included in the U.S. human diet; and (2) plants serving as animal feed. Plants used vary according to availability of data.

b. **Assumptions/Limitations** - Assumes an uptake factor that is constant over all soil concentrations. The uptake factor chosen for the human diet is assumed to be representative of all crops (except fruits) in the human diet. The uptake factor chosen for the animal diet is assumed to be representative of all crops in the animal diet. See also Index 6 for consideration of phytotoxicity.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Uptake factor of pollutant in plant tissue (UP)**

Animal Diet:
Spinach 0.42 μg/g tissue DW (μg/g soil DW)$^{-1}$

Human Diet:
Carrot 1.8 μg/g tissue DW (μg/g soil DW)$^{-1}$

Spinach was selected to represent a plant consumed by herbivorous animals because no data were immediately available for crops normally fed to animals. It is assumed that the uptake factor for spinach is similar to uptake factors for more representative plants. Connor (1984) reported uptake factors of 0.02 to 0.05 (ratio of plant to soil concentration, fresh weight:fresh weight). Since it was noted by Connor that conversion from dry-dry ratios to fresh-fresh ratios had been done by multiplying by 0.12, the inverse was assumed for conversion of fresh-fresh to dry-dry weights. When converted to a dry-dry ratio, the highest, and thus most conservative, uptake factor for spinach was 0.42.

Carrots were selected to represent a plant consumed by humans. The uptake factor for carrot roots ranged from 0.09 to 0.22 (fresh-fresh ratio) when grown in sand and was 0.01 when grown in compost (Connor, 1984). As in the case of spinach, ratios for fresh weights were converted to ratios of dry weights by dividing by a factor of 0.12. The uptake factor selected was the highest, and thus the most conservative, value. (See Section 4, p. 4-9.)

d. **Index 5 Values (μg/g DW)**

Diet	Sludge Concentration	Sludge Application Rate (mt/ha)			
		0	5	50	500
Animal	Typical	0.042	0.042	0.042	0.043
	Worst	0.042	0.044	0.061	0.045
Human	Typical	0.18	0.18	0.18	0.18
	Worst	0.18	0.19	0.26	0.19

e. **Value Interpretation** - Value equals the expected concentration in tissues of plants grown in sludge-amended soil. However, any value exceeding the value of Index 6 for the same or a similar plant species may be unrealistically high because it would be precluded by phytoxicity.

f. **Preliminary Conclusion** - Landspreading of sludge containing a worst concentration of BaP is expected to slightly increase the tissue concentration of BaP in plants in the animal and human diet.

3. **Index of Plant Concentration Permitted by Phytotoxicity (Index 6)**

a. **Explanation** - The index value is the maximum tissue concentration, in μg/g DW, associated with phytotoxicity in the same or similar plant species used in Index 5. The purpose is to determine whether the plant tissue concentrations determined in Index 5 for high applications are realistic, or whether such concentrations would be precluded by phytotoxicity. The maximum concentration should be the highest at which some plant growth still occurs (and thus consumption of tissue by animals is possible) but above which consumption by animals is unlikely.

b. **Assumptions/Limitations** - Assumes that tissue concentration will be a consistent indicator of phytotoxicity.

c. **Data Used and Rationale**

i. **Maximum plant tissue concentration associated with phytoxicity (PP)** - Data not immediately available.

d. **Index 6 Values (μg/g DW)** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Value equals the maximum plant tissue concentration which is permitted by phytotoxicity. Value is compared with values for the same or similar plant species given by Index 5. The lowest of the two indices indicates the maximal increase that can occur at any given application rate.

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

D. Effect on Herbivorous Animals

1. Index of Animal Toxicity Resulting from Plant Consumption (Index 7)

a. **Explanation** - Compares pollutant concentrations expected in plant tissues grown in sludge-amended soil with feed concentration shown to be toxic to wild or domestic herbivorous animals. Does not consider direct contamination of forage by adhering sludge.

b. **Assumptions/Limitations** - Assumes pollutant form taken up by plants is equivalent in toxicity to form used to demonstrate toxic effects in animal. Uptake or toxicity in specific plants or animals may be estimated from other species.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)**

The pollutant concentration values used are those Index 5 values for an animal diet (see Section 3, p. 3-5).

ii. **Feed concentration toxic to herbivorous animal (TA) = 40 µg/g DW**

A concentration of 40 µg/g was the lowest dietary concentration associated with adverse effects. This concentration was associated with carcinogenic effects in mice after oral administration for 110 days (National Academy of Sciences (NAS), 1977). No tumors were found in mice fed up to 30 ppm in the diet for 110 days, while mice fed diets containing 50 to 250 µg/g for 100 to 197 days showed greater than 70% incidence of stomach tumors (U.S. EPA, 1980). (See Section 4, p. 4-10.)

d. **Index 7 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0.0011	0.0011	0.0011	0.0011
Worst	0.0011	0.0011	0.0015	0.0011

e. **Value Interpretation** - Value equals factor by which expected plant tissue concentration exceeds that which is toxic to animals. Value > 1 indicates a toxic hazard may exist for herbivorous animals.

f. **Preliminary Conclusion** - The concentration of BaP in plants grown on sludge-amended soil is not expected to exceed the dietary concentration toxic to herbivorous animals.

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Explanation** - Calculates the amount of pollutant in a grazing animal's diet resulting from sludge adhesion to forage or from incidental ingestion of sludge-amended soil and compares this with the dietary toxic threshold concentration for a grazing animal.

b. **Assumptions/Limitations** - Assumes that sludge is applied over and adheres to growing forage, or that sludge constitutes 5 percent of dry matter in the grazing animal's diet, and that pollutant form in sludge is equally bioavailable and toxic as form used to demonstrate toxic effects. Where no sludge is applied (i.e., 0 mt/ha), assumes diet is 5 percent soil as a basis for comparison.

c. **Data Used and Rationale**

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

Typical	0.143 μg/g DW
Worst	1.937 μg/g DW

See Section 3, p. 3-1.

ii. **Fraction of animal diet assumed to be soil (GS) = 5%**

Studies of sludge adhesion to growing forage following applications of liquid or filter-cake sludge show that when 3 to 6 mt/ha of sludge solids is applied, clipped forage initially consists of up to 30 percent sludge on a dry-weight basis (Chaney and Lloyd, 1979; Boswell, 1975). However, this contamination diminishes gradually with time and growth, and generally is not detected in the following year's growth. For example, where pastures amended at 16 and 32 mt/ha were grazed throughout a growing season (168 days), average sludge content of forage was only 2.14 and 4.75 percent, respectively (Bertrand et al., 1981). It seems reasonable to assume that animals may receive long-term dietary exposure to 5 percent sludge if maintained on a forage to which sludge is regularly applied. This estimate of 5 percent sludge is used regardless of application rate, since the above studies did not show a clear relationship between application rate and initial contamination, and since adhesion is not cumulative yearly because of die-back.

Studies of grazing animals indicate that soil ingestion, ordinarily <10 percent of dry weight of diet, may reach as high as 20 percent for cattle and 30 percent for sheep during winter months when forage is reduced (Thornton and Abrams, 1983). If the soil were sludge-amended, it is conceivable that up to 5 percent sludge may be ingested in this manner as well. Therefore, this value accounts for either of these scenarios, whether forage is harvested or grazed in the field.

iii. **Feed concentration toxic to herbivorous animal (TA)** = 40 μg/g DW

See Section 3, p. 3-7.

d. **Index 8 Values**

Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Typical	0	0.00018	0.00018	0.00018
Worst	0	0.0024	0.0024	0.0024

e. **Value Interpretation** - Value equals factor by which expected dietary concentration exceeds toxic concentration. Value > 1 indicates a toxic hazard may exist for grazing animals.

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to pose a toxic hazard due to BaP for grazing animals that incidentally ingest sludge-amended soil.

E. **Effect on Humans**

1. **Index of Human Cancer Risk Resulting from Plant Consumption (Index 9)**

a. **Explanation** - Calculates dietary intake expected to result from consumption of crops grown on sludge-amended soil. Compares dietary intake with the cancer risk-specific intake (RSI) of the pollutant.

b. **Assumptions/Limitations** - Assumes that all crops are grown on sludge-amended soil and that all those considered to be affected take up the pollutant at the same rate. Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)**

The pollutant concentration values used are those Index 5 values for a human diet (see Section 3, p. 3-5).

ii. **Daily human dietary intake of affected plant tissue (DT)**

Toddler	74.5 g/day
Adult	205 g/day

The intake value for adults is based on daily intake of crop foods (excluding fruit) by vegetarians (Ryan et al., 1982); vegetarians were chosen to represent the worst case. The value for toddlers is based on the FDA Revised Total Diet (Pennington, 1983) and food groupings listed by the U.S. EPA (1984a). Dry weights for individual food groups were estimated from composition data given by the U.S. Department of Agriculture (USDA) (1975). These values were composited to estimate dry-weight consumption of all non-fruit crops.

iii. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.29 µg/day
Adult	0.88 µg/day

U.S. EPA (1980) reported that daily intake of BaP from food ranged from 0.16 to 1.6 µg/day. The daily intake was obtained by averaging the two values at the extremes of the range. The value for toddlers was calculated by assuming that daily intake of BaP is one third of the adult daily intake. (See Section 4, p. 4-3.)

iv. **Cancer potency** = 11.5 $(mg/kg/day)^{-1}$

Cancer potency for ingestion of BaP was calculated by U.S. EPA (1980). The slope was based on a study by Neal and Rigdon (1967, as cited in U.S. EPA, 1980) in which BaP was fed to mice at concentrations ranging from 1 to 250 ppm in the diet for approximately 110 days. Results showed a significant increase in the incidence of stomach tumors at several doses. In the four highest dose groups receiving 5.85, 6.5, 13.0, and 13.5 mg/kg body weight (bw)/day, tumors developed in 4 of 40, 24 of 34, 19 of 23, and 66 of 73 mice, respectively, compared to 0 of 289 in controls. (See Section 4, p. 4-5.)

v. **Cancer risk-specific intake (RSI) =** 0.00607 μg/day

The RSI is the pollutant intake value which results in an increase in cancer risk of 10^{-6} (1 per 1,000,000). The RSI is calculated from the cancer potency using the following formula:

$$RSI = \frac{10^{-6} \times 70 \text{ kg} \times 10^3 \text{ μg/mg}}{\text{Cancer potency}}$$

d. **Index 9 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	2300	2300	2300	2300
	Worst	2300	2400	3200	2400
Adult	Typical	6200	6200	6300	6400
	Worst	6200	6500	8900.	6700

e. **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 mt/ha indicates the degree to which any hazard is due to sludge application, as opposed to pre-existing dietary sources.

f. **Preliminary Conclusion** - For toddlers who consume plants grown in sludge-amended soil, an increase in the risk of cancer due to BaP is expected when sludges containing the worst-case concentration of BaP are landspread. For adults, an increase in the risk of cancer is expected when sludges containing a typical concentration of BaP are applied at the rates of 50 and 500 mt/ha, and when sludges containing a worst-case concentration are applied at any rate (5 to 500 mt/ha).

2. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)**

a. **Explanation** - Calculates human dietary intake expected to result from pollutant uptake by domestic animals given feed grown on sludge-amended soil (crop or pasture land) but not directly contaminated by adhering sludge. Compares expected intake with RSI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals receiving all their feed from sludge-amended soil. Assumes that all animal products consumed take up the pollutant at the highest rate observed for muscle of any commonly consumed species or at the rate observed for beef liver or dairy products (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Concentration of pollutant in plant grown in sludge-amended soil (Index 5)**

The pollutant concentration values used are those Index 5 values for an animal diet (see Section 3, p. 3-5).

ii. **Uptake factor of pollutant in animal tissue (UA)** - Data not immediately available.

iii. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	43.7 g/day
Adult	88.5 g/day

The fat intake values presented, which comprise meat, fish, poultry, eggs and milk products, are derived from the FDA Revised Total Diet (Pennington, 1983), food groupings listed by the U.S. EPA (1984a) and food composition data given by USDA (1975). Adult intake of meats is based on males 25 to 30 years of age and that for milk products on males 14 to 16 years of age, the age-sex groups with the highest daily intake. Toddler intake of milk products is actually based on infants, since infant milk consumption is the highest among that age group (Pennington, 1983).

iv. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.29 μg/day
Adult	0.88 μg/day

See Section 3, p. 3-10.

v. **Cancer risk-specific intake (RSI)** = 0.00607 μg/day

See Section 3, p. 3-11.

d. **Index 10 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

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

3. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Explanation** - Calculates human dietary intake expected to result from consumption of animal products derived from grazing animals incidentally ingesting sludge-amended soil. Compares expected intake with RSI.

b. **Assumptions/Limitations** - Assumes that all animal products are from animals grazing sludge-amended soil, and that all animal products consumed take up the pollutant at the highest rate observed for muscle of any commonly consumed species or at the rate observed for beef liver or dairy products (whichever is higher). Divides possible variations in dietary intake into two categories: toddlers (18 months to 3 years) and individuals over 3 years old.

c. **Data Used and Rationale**

i. **Animal tissue** - Data not immediately available.

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

Typical	0.143 μg/g DW
Worst	1.937 μg/g DW

See Section 3, p. 3-1.

iii. **Background concentration of pollutant in soil (BS)** = 0.1 μg/g DW

See Section 3, p. 3-2.

iv. **Fraction of animal diet assumed to be soil (GS)** = 5%

See Section 3, p. 3-8.

v. **Uptake factor of pollutant in animal tissue (UA)** - Data not immediately available.

vi. **Daily human dietary intake of affected animal tissue (DA)**

Toddler	39.4 g/day
Adult	82.4 g/day

The affected tissue intake value is assumed to be from the fat component of meat only (beef, pork, lamb, veal) and milk products (Pennington, 1983). This is a slightly more limited choice than for Index 10. Adult intake of meats is based on males 25 to 30 years of age and the intake for milk products on males 14 to 16 years of age, the age-sex groups with the highest daily intake. Toddler intake of milk products is actually based on infants, since infant milk consumption is the highest among that age group (Pennington, 1983).

vii. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.29 μg/day
Adult	0.88 μg/day

See Section 3, p. 3-10.

viii. **Cancer risk-specific intake (RSI)** = 0.00607 μg/day

See Section 3, p. 3-11.

d. **Index 11 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

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

4. **Index of Human Cancer Risk from Soil Ingestion (Index 12)**

a. **Explanation** - Calculates the amount of pollutant in the diet of a child who ingests soil (pica child) amended with sludge. Compares this amount with RSI.

b. **Assumptions/Limitations** - Assumes that the pica child consumes an average of 5 g/day of sludge-amended soil. If the RSI specific for a child is not available, this index assumes the RSI for a 10 kg child is the same as that for a 70 kg adult. It is thus assumed that uncertainty factors used in deriving the RSI provide protection for the child, taking into account the smaller body size and any other differences in sensitivity.

c. **Data Used and Rationale**

i. **Concentration of pollutant in sludge-amended soil (Index 1)**

See Section 3, p. 3-2.

ii. **Assumed amount of soil in human diet (DS)**

Pica child	5 g/day
Adult	0.02 g/day

The value of 5 g/day for a pica child is a worst-case estimate employed by U.S. EPA's Exposure Assessment Group (U.S. EPA, 1983a). The value of 0.02 g/day for an adult is an estimate from U.S. EPA, 1984a.

iii. **Average daily human dietary intake of pollutant (DI)**

Toddler	0.29 µg/day
Adult	0.88 µg/day

See Section 3, p. 3-10.

iv. **Cancer risk-specific intake (RSI)** = 0.00607 µg/day

See Section 3, p. 3-11.

d. **Index 12 Values**

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	130	130	130	130
	Worst	130	130	170	140
Adult	Typical	150	150	150	150
	Worst	150	150	150	150

e. **Value Interpretation** - Same as for Index 9.

f. **Preliminary Conclusion** - An increase in the risk of cancer is expected to occur for toddlers who ingest sludge-amended soil when sludges containing atypically high concentrations of BaP are applied to soil at high rates (50 and 500 mt/ha).

5. **Index of Aggregate Human Cancer Risk (Index 13)**

a. **Explanation** - Calculates the aggregate amount of pollutant in the human diet resulting from pathways described in Indices 9 to 12. Compares this amount with RSI.

b. **Assumptions/Limitations** - As described for Indices 9 to 12.

c. **Data Used and Rationale** - As described for Indices 9 to 12.

d. **Index 13 Values** - Values were not calculated due to lack of data.

e. **Value Interpretation** - Same as for Index 9.

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

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, 1983b). 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 (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	0.143 mg/kg DW
Worst	1.937 mg/kg DW

See Section 3, p. 3-1.

(b) Soil half-life of pollutant ($t_{\frac{1}{2}}$) = 69.3 days

The value given in days is the same as that reported in years (0.18986) in Section 3, p. 3-2.

(c) Degradation rate (μ) = 0.01 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:

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

(d) Organic carbon partition coefficient (K_{oc}) = 630,000 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 ($K_{oc} \times f_{oc}$) 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 Lyman (1982).

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 (1983b).

(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 (1983b).

(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 μg/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** - The concentration of BaP in groundwater at the well is expected to increase when sludge is disposed in landfills. The greatest increase in the groundwater concentration is expected when worst-case conditions exist in both the unsaturated and saturated zones.

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. 3-25.

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) = 0.88 μg/day**

See Section 3, p. 3-10.

d. **Cancer potency** = 11.5 $(mg/kg/day)^{-1}$

See Section 3, p. 3-11.

e. **Cancer risk-specific intake (RSI)** = 0.00607 µg/day

See Section 3, p. 3-11.

4. **Index 2 Values** - See Table 3-1.

5. **Value Interpretation** - Value >1 indicates a potential increase in cancer risk of 10^{-6} (1 in 1,000,000). The null index value should be used as a basis for comparison to indicate the degree to which any risk is due to landfill disposal, as opposed to preexisting dietary sources.

6. **Preliminary Conclusion** - The risk of cancer due to BaP in groundwater is expected to increase above the preexisting risk due to dietary sources only when sludges with atypically high concentrations of BaP are disposed in landfills which are characterized by worst-case conditions.

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.

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)	1.3×10^{-4}	1.8×10^{-3}	3.3×10^{-4}	3.9×10^{-3}	4.3×10^{-4}	4.6×10^{-4}	11	0
Index 2 Value	150	150	150	150	150	150	3800	150

[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).

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	0.143 mg/kg DW
Worst	1.937 mg/kg DW

See Section 3, p. 3-1.

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 μg/m^3
Worst 16.0 μg/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) = 0.0005 μg/m^3**

Average concentrations of BaP in urban areas of the United States were 0.0032 μg/m^3 in 1966, 0.0021 μg/m^3 in 1970, and 0.0005 in 1976 (U.S. EPA, 1980). These data indicate a declining trend. Therefore, the value selected to represent the background concentration of BaP in urban air is the most recent of these three values. (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	1.0	1.0	1.6
	Worst	1.0	1.5	9.6
Worst	Typical	1.0	1.1	3.5
	Worst	1.0	2.9	35

[a] The typical (3.4 μg/m^3) and worst (16.0 μg/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** - The concentration of BaP in air is expected to increase as the sludge feed rate and concentration of BaP in sludge increase. An exception is found when sludge containing a typical concentration of BaP is burned at a low rate (2660 kg/hr DW); in this case no increase is expected.

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}.

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. 3-27.

   b. **Background concentration of pollutant in urban air (BA)** = 0.0005 $\mu g/m^3$

   See Section 3, p. 3-27.

   c. **Cancer potency** = 4.3 $(mg/kg/day)^{-1}$

   The cancer potency for inhalation of BaP was derived by U.S. EPA (1984b) based on a study by Thyssen et al. (1981, as cited in U.S. EPA, 1984b) in which Syrian golden hamsters were exposed to BaP by inhalation. Dose levels of 2.2, 9.5, and 46.5 mg/m^3 produced tumors in 0 of 27, 9 of 26, and 13 of 25 animals, respectively. No tumors were found in the 27 controls. (See Section 4, p. 4-6.)

   d. **Exposure criterion (EC)** = 0.00081 $\mu g/m^3$

   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**

Fraction of Pollutant Emitted Through Stack	Sludge Concentration	Sludge Feed Rate (kg/hr DW)[a] 0	2660	10,000
Typical	Typical	0.62	0.64	1.0
	Worst	0.62	0.92	5.9
Worst	Typical	0.62	0.71	2.2
	Worst	0.62	1.8	22

[a] The typical (3.4 μg/m^3) and worst (16.0 μg/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 > 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** - Incineration of sludge is expected to increase the cancer risk due to inhalation of BaP above the risk posed by background urban air concentrations of BaP. This increase may be substantial when sludge containing a high concentration of BaP is incinerated at a high feed rate and a large fraction of the pollutant is emitted through the stack.

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 additional 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	0.143 mg/kg DW
Worst	1.937 mg/kg DW

See Section 3, p. 3-1.

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:

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

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	0.00029	0.00029
	Worst	0.0	0.0039	0.0039
Worst	Typical	0.0	0.0024	0.0024
	Worst	0.0	0.033	0.033

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

7. **Preliminary Conclusion** - Only slight increases of BaP occur after the dumping of sludges and initial mixing.

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. 3-30 to 3-32.

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

   See Section 3, p. 3-33.

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	0.000078	0.00016
	Worst	0.0	0.0011	0.0021
Worst	Typical	0.0	0.00068	0.0014
	Worst	0.0	0.0092	0.018

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

7. **Preliminary Conclusion** - Only slight increases of seawater BaP concentrations occur after a 24-hour dumping cycle.

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 BaP, 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. 3-33.

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 polynuclear aromatic hydrocarbons (PAHs).

No BaP-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	0.00000095	0.00000095
	Worst	0.0	0.000013	0.000013
Worst	Typical	0.0	0.0000081	0.0000081
	Worst	0.0	0.00011	0.00011

5. **Value Interpretation** - Value equals the factor by which the expected seawater concentration increase in BaP 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 in the incremental hazard to aquatic life are evident for worst-concentration sludges dumped at the typical and worst sites. No increase is apparent for typical sludges dumped at typical sites.

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. 3-34.

   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) =** 11,100 L/kg

The value chosen is the weighted average BCF of BaP 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 BaP induced by ingestion of contaminated water and aquatic organisms. Although no measured steady-state BCF for BaP is available, a BCF value for aquatic organisms containing about 7.6% 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% lipid content of consumed fish and shellfish. It should be noted, however, that the resulting estimated weighted average BCF of 11,100 L/kg is a possible overestimation. 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 (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)** = 0.88 μg/day

See Section 3, p. 3-10.

f. **Cancer potency** = 11.5 $(mg/kg/day)^{-1}$

See Section 3, p. 3-11.

g. **Cancer risk-specific intake (RSI)** = 0.00607 μg/day

See Section 3, p. 3-11.

4. **Index 4 Values**

Disposal Conditions and Site Characteristics	Sludge Concentration[a]	Seafood Intake[a,b]	Sludge Disposal Rate (mt DW/day) 0	825	1650
Typical	Typical	Typical	140	140	140
	Worst	Worst	140	150	160
Worst	Typical	Typical	140	140	140
	Worst	Worst	140	170	200

[a] All possible combinations of these values are not presented. Additional combinations may be calculated using the formulae in the Appendix.

[b] Refers to both the dietary consumption of seafood (QF) and the fraction of consumed seafood originating from

the disposal site (FS). "Typical" indicates the use of the typical-case values for both of these parameters; "worst" indicates the use of the worst-case values for both.

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 pre-existing dietary sources.

6. **Preliminary Conclusion** - Increases in human health risk are apparent from consuming seafood taken from typical or worst sites after dumping of sludges containing worst concentrations of BaP.

SECTION 4

PRELIMINARY DATA PROFILE FOR BENZO(A)PYRENE IN MUNICIPAL SEWAGE SLUDGE

I. OCCURRENCE

A. Sludge

1. Frequency of Detection

BaP was detected in 21 of 437 samples (5%) and 3 of 42 samples (7%) from 50 POTWs.	U.S. EPA, 1982 (pp. 42 and 50)

2. Concentration

Dry-weight sludge concentrations of BaP found in a survey of POTWs: Median 0.143 µg/g DW 95th percentile 1.937 µg/g DW Mean 0.561 µg/g DW Minimum Not detected Maximum 2.918 µg/g DW	Statistically derived from data presented in U.S. EPA, 1982
Wet-weight sludge concentrations: 1 to 490 µg/L from 437 samples from the 40-city study.	U.S. EPA, 1982 (p. 42)

B. Soil - Unpolluted

1. Frequency of Detection

Data not immediately available.

2. Concentration

The concentration in the upper layers of of the earth is in the range of 0.100 to 1.000 µg/g of carcinogenic PAHs and results from the activity of soil bacteria and from decayed plants.	Suess, 1976 (p. 244)

C. Water - Unpolluted

1. Frequency of Detection

0 of 87 systems tested serving populations of >75,000 were positive for BaP.	Pendygraft et al., 1979 (pp. 177 and 181)

2. **Concentration**

a. **Freshwater**

Groundwater will have a carcinogenic PAH concentration of 0.001 to 0.010 µg/L. Freshwater lakes will have a PAH concentration of 0.010 to 0.025 µg/L.	Suess, 1976 (p. 244)

b. **Seawater**

Data not immediately available.

c. **Drinking Water**

Water = 0.0011 µg/day	U.S. EPA, 1980 (p. 112)

D. **Air**

1. **Frequency of Detection**

Data not immediately available.

2. **Concentration**

a. **Urban**

Philadelphia average BaP concentrations for 1967-1969 for the four quarters of the year were 6.3, 1.7, 1.4, and 6.7 ng/m^3.	Suess, 1976 (p. 244)
Pittsburgh average BaP concentrations for 1967-1969 for the four quarters of the year were 21.3, 18.3, 6.0, and 9.4 ng/m^3.	Suess, 1976 (p. 246)
BaP in air of U.S. cities (ng/m^3):	U.S. EPA, 1980 (p. C-32)

1966	1970	1976
3.2	2.1	0.5

b. Rural

0.1 to 0.2 ng/m^3	Suess, 1976 (p. 244)
BaP in air of U.S. rural areas ng/m^3:	U.S. EPA, 1980 (p. C-32)

1966	1970	1976
0.4	0.2	0.1

E. Food

1. Total Average Intake

Data not immediately available.

2. Concentration

Average Daily Intake of BaP: Water = 0.0011 µg/day Food = 0.160 to 1.6 µg/day Estimated average adult intake for food = 0.88 µg/day (based on mean of the range values) Estimated average toddler intake = 0.29 µg/day (based on assumption that toddler intake is 1/3 of adult intake)	U.S. EPA, 1980 (p. C-112)
A test of 39 beers showed no BaP above a level of 0.5 ng/g.	Joe et al., 1981 (p. 644)
BaP concentrations in vegetable oils and margarine showed BaP values of 0.2 to 8.0 ng/g.	U.S. EPA, 1980 (p. C-13)
BaP concentrations in smoked fish ranged from trace amounts to 0.6 ng/g.	U.S. EPA, 1980 (p. C-14)
BaP concentrations in smoked meat ranged from trace amounts to 10.5 ng/g.	U.S. EPA, 1980 (p. C-21)
BaP concentrations in fruits from unpolluted environments ranged from trace amounts to 29.7 ng/g (data for Europe and Japan).	U.S. EPA, 1980 (p. C-24)
BaP concentrations in cereals showed values of 0.1 to 60 ng/g (data for Europe and Japan).	U.S. EPA, 1980 (p. C-25)

BaP concentrations in vegetables from unpolluted environments showed values of 0.01 to 24.3 ng/g (data for Europe and Japan). — U.S. EPA, 1980 (p. C-26)

II. HUMAN EFFECTS

A. Ingestion

1. Carcinogenicity

a. Qualitative Assessment

Numerous polycyclic aromatic compounds (such as BaP) are distinctive in their ability to produce tumors in skin and most epithelial tissues of almost all species tested. Latency periods can be short, and tumors produced may resemble human carcinomas. — U.S. EPA, 1980 (p. C-72)

Carcinogenicity of BaP has not been studied as thoroughly by oral intake as by other routes of administration; however, tumors of various sites result when BaP is administered orally to rodents. Tumors include stomach tumors, leukemias, lung adenomas, esophagal tumors, and intestinal tumors. With oral, intratracheal, and intravenous routes of administration, BaP is less effective than other PAHs (e.g., 7,12-dimethylenz[a]anthracene, 3-methylcholanthrene, and dibenz(a,h)-anthracene) in producing carcinomas, but has remarkable potency for induction of skin tumors in mice. — U.S. EPA, 1980 (pp. C-86, C-88, C-89)

b. Potency

Cancer potency = 11.5 $(mg/kg/day)^{-1}$ — U.S. EPA, 1980 (p. C-180)

The cancer potency was derived from data reported by Neal and Rigdon (1967), as cited in U.S. EPA (1980). In this study, BaP was fed to CFW mice at dietary concentrations ranging from 1 to 250 ppm for approximately 110 days. Stomach tumors (primarily squamous cell papillomas, but some carcinomas) appeared with an incidence statistically higher than controls at several doses.

Tumor incidences:

Dose (mg/kg/day)	Incidence (No. Responding/No. Tested)
0.0	0/289
0.13	0/25
1.3	0/24
2.6	1/23
3.9	0/37
5.2	1/40
5.85	4/40
6.5	24/34
13.0	19/23
13.5	66/73

2. Chronic Toxicity

a. ADI

Not derived since cancer potency was used to assess hazard.

b. Effects

See Section 4, p. 4-4.

3. Absorption Factor

Intestinal transport occurs readily, primarily by passive diffusion. — U.S. EPA, 1980 (p. C-37)

Rats given BaP by gavage in starch solution (100 mg) or in the diet (250 mg) absorbed approximately 50 percent of the administered compound. — U.S. EPA, 1984b (p. 5)

4. Existing Regulations

For maximum protection from carcinogenic effects, ambient water concentration for PAHs should be zero, assuming no threshold. Criteria for levels which may result in incremental increase in risk of cancer over the lifetime of 10^{-5}, 10^{-6}, and 10^{-7} are 28.0 ng/L, 2.8 ng/L, and 0.28 ng/L, respectively. — U.S. EPA, 1980 (p. vi)

1970 World Health Organization European Standards for Drinking Water recommends PAH concentration not to exceed 0.2 μg/L. — U.S. EPA, 1980 (p. C-108)

B. Inhalation

1. Carcinogenicity

a. Qualitative Assessment

BaP was the first carcinogenic hydrocarbon identified in soot.

Intratracheal instillation of BaP in Syrian golden hamsters showed a dose response relationship for development of respiratory tumors. Also, co-administration of carrier particles such as Fe_2O_3 can markedly increase tumor incidence depending on the conditions of the experiment and physical characteristics of the particle. — U.S. EPA, 1980 (pp. C-89 and C-91)

b. Potency

Cancer potency = 4.3 $(mg/kg/day)^{-1}$ — U.S. EPA, 1984b (p. 32)

Cancer potency was derived by U.S. EPA (1984b) based on a study by Thyssen et al. (1981) in which Syrian golden hamsters were exposed to BaP by inhalation at levels of 0, 2.2, 9.5, or 46.5 mg/m^3 for 59.5 to 96.4 weeks. Incidence of tumors were:

Dose (mg/m^3)	Incidence (No. Responding/No. Tested)
0	0/27
2.2	0/27
9.5	9/26
46.5	13/25

2. Chronic Toxicity

a. Inhalation Threshold or MPIH

Data not assessed since the evaluation was based on carcinogenicity.

b. Effects

See Section 4, p. 4-6.

3. Absorption Factor

There is ample evidence that BaP is easily absorbed through the lungs.	U.S. EPA, 1980 (p. C-37)

4. Existing Regulations

Substance	Exposure Limit	Agency	
Coke Oven Emissions	150 μg/m^3, 8-hr time-weighted average (TWA)	U.S. Occupational Safety and Health Administration	U.S. EPA, 1980 (p. C-108)
Coal Tar Products	0.1 mg/m^3, 10-hr TWA	U.S. National Institute for Occupational Safety and Health	
Coal Tar Pitch of Volatiles	0.2 mg/m^3 (benzene soluble fraction 8-hr TWA)	American Conference of Governmental and Industrial Hygienists	

III. PLANT EFFECTS

A. Phytotoxicity

Data not immediately available.

B. Uptake

See Table 4-1.

IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. Toxicity

See Table 4-2.

B. Uptake

From available information on excretion of PAH in animals, extensive bioaccumulation is not likely to occur.	U.S. EPA, 1980 (p. C-49)

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. No chronic data are presently available.	U.S. EPA, 1980 (pp. B-1 and B-2)

B. Uptake

The estimated weighted average BCF of BaP for the edible portion of all freshwater and estuarine aquatic organisms consumed by U.S. citizens is 11,100.	U.S. EPA, 1980 (p. C-19)

VI. SOIL BIOTA EFFECTS

Data not immediately available.

VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Molecular weight: 252.32 BaP is very persistent in water and is soluble at 0.004 mg/L at 27°C	NAS, 1977 (p. 691)
Degradation rate: 0.01 day^{-1}	Herbes and Schwall, 1978
K_{oc} (organic carbon partition coefficient) = 630,000 mL/g	Lyman, 1982

TABLE 4-1. UPTAKE OF BENZO(A)PYRENE BY PLANTS

Plant/Tissue	Soil Type	Chemical Form Applied	Soil Concentration (μg/g DW)	Tissue Concentration (μg/g DW)	Uptake Factor[a]	References
Carrots/roots	sand	BaP	NR[b]	NR	0.75-1.8(0.09-0.22)	Connor, 1984 (p. 48)
Carrots/roots	compost	BaP	NR	NR	0.08 (0.01)	Connor, 1984 (p. 48)
Carrots/foliage	sand	BaP	NR	NR	0.08 (0.01)	Connor, 1984 (p. 48)
Carrots/foliage	compost	BaP	NR	NR	0.08 (0.01)	Connor, 1984 (p. 48)
Radishes/roots	NR	BaP	NR	NR	0.08-0.16(0.01-0.02)	Connor, 1984 (p. 48)
Radishes/foliage	NR	BaP	NR	NR	0.08 (0.01)[a]	Connor, 1984 (p. 48)
Spinach/leaf	NR	BaP	NR	NR	0.16-0.42(0.02-0.05)	Connor, 1984 (p. 48)

[a] Values were reported as plant to soil concentration ratio (fresh weight:fresh weight, FW:FW) in the original reference. These values are presented in parentheses. Values were converted to a DW:DW ratio by dividing by 0.12, since Connor (1984) had multiplied by 0.12 to convert from DW:DW to FW:FW.

[b] NR = Not reported.

TABLE 4-2. TOXICITY OF BENZO(A)PYRENE TO DOMESTIC ANIMALS AND WILDLIFE

Species (N)[a]	Chemical Form Fed	Feed Concentration (µg/g DW)	Water Concentration (mg/L)	Daily Intake (mg/kg)	Duration of Study	Effects	References
Rat (40)	BaP	NR[b]	NR	2.5	NR	Papillomas in stomach of 3 of 40 animals	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	50-250	NR	NR	110-197 days	>70% incidence of stomach tumors	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	30	NR	NR	110 days	No tumors	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	250	NR	NR	1 day	No tumors	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	250	NR	NR	2-4 days	10% tumor incidence	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	250	NR	NR	5-7 days	30-40% tumor incidence	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	250	NR	NR	30 days	100% tumor incidence	U.S. EPA, 1980 (p. C-88)
Mouse	BaP	40-45	NR	NR	110 days	Carcinogenic effects	NAS, 1977 (p. 692)

[a] N = Number of experimental animals when reported.

[b] NR = Not reported.

SECTION 5

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APPENDIX

PRELIMINARY HAZARD INDEX CALCULATIONS FOR BENZO(A)PYRENE IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Benzo(a)pyrene

1. Index of Soil Concentration (Index 1)

a. Formula

$$CS_s = \frac{(SC \times AR) + (BS \times MS)}{AR + MS}$$

$$CS_r = CS_s \, [1 + 0.5^{(1/t_{\frac{1}{2}})} + 0.5^{(2/t_{\frac{1}{2}})} + \ldots + 0.5^{(n/t_{\frac{1}{2}})}]$$

where:

CS_s = Soil concentration of pollutant after a single year's application of sludge (μg/g DW)
CS_r = Soil concentration of pollutant after the yearly application of sludge has been repeated for n + 1 years (μg/g DW)
SC = Sludge concentration of pollutant (μg/g DW)
AR = Sludge application rate (mt/ha)
MS = 2000 mt ha/DW = assumed mass of soil in upper 15 cm
BS = Background concentration of pollutant in soil (μg/g DW)
$t_{\frac{1}{2}}$ = Soil half-life of pollutant (years)

b. Sample calculation

CS_s is calculated for AR = 0, 5, 50 mt/ha and 500 mt/ha*.

$$0.100 = \frac{(0.143 \text{ μg/g DW} \times 5 \text{ mt/ha}) + (0.1 \text{ μg/g DW} \times 2000 \text{ mt/ha})}{(5 \text{ mt/ha DW} + 2000 \text{ mt/ha DW})}$$

CS_r is calculated for AR = 5 mt/ha applied for 100 years

$$0.103 \text{ μg/g DW} = 0.100 \text{ μg/g DW} \, [1 + 0.5^{(1/0.18986)} + 0.5^{2/0.18986)} + \ldots + 0.5^{(99/0.18986)}]$$

B. Effect on Soil Biota and Predators of Soil Biota

1. Index of Soil Biota Toxicity (Index 2)

a. Formula

$$\text{Index 2} = \frac{I_1}{TB}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
TB = Soil concentration toxic to soil biota (μg/g DW)

b. Sample calculation - Values were not calculated due to lack of data.

2. Index of Soil Biota Predator Toxicity (Index 3)

a. Formula

$$\text{Index 3} = \frac{I_1 \times UB}{TR}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
UB = Uptake factor of pollutant in soil biota (μg/g tissue DW [μg/g soil DW]$^{-1}$)
TR = Food concentration toxic to predator (μg/g DW)

b. Sample calculation - Values were not calculated due to lack of data.

C. Effect on Plants and Plant Tissue Concentration

1. Index of Phytotoxic Soil Concentration (Index 4)

a. Formula

$$\text{Index 4} = \frac{I_1}{TP}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
TP = Soil concentration toxic to plants (μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

2. **Index of Plant Concentration Increment Caused by Uptake (Index 5)**

a. **Formula**

Index 5 = I_1 x UP

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
UP = Uptake factor of pollutant in plant tissue (μg/g tissue DW [μg/g soil DW]$^{-1}$)

b. **Sample Calculation**

0.042 μg/g DW = 0.100 μg/g DW x 0.42 μg/g tissue DW (μg/g soil DW)$^{-1}$

3. **Index of Phytotoxic Plant Tissue Concentration (Index 6)**

a. **Formula**

Index 6 = PP

where:

PP = Maximum plant tissue concentration associated with phytotoxicity μg/g DW)

b. **Sample calculation** - Values were not calculated due to lack of data.

D. **Effect on Herbivorous Animals**

1. **Index of Animal Toxicity Resulting from Plant Consumption (Index 7)**

a. **Formula**

Index 7 $\frac{I_5}{TA}$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation**

$$0.0011 = \frac{0.042\ \mu g/g\ DW}{40\ \mu g/g\ DW}$$

2. **Index of Animal Toxicity Resulting from Sludge Ingestion (Index 8)**

a. **Formula**

If AR = 0; Index 8 = 0

$$\text{If AR} \neq 0;\ \text{Index 8} = \frac{SC \times GS}{TA}$$

where:

AR = Sludge application rate (mt DW/ha)
SC = Sludge concentration of pollutant (μg/g DW)
GS = Fraction of animal diet assumed to be soil
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation**

If AR = 0; Index 8 = 0

$$\text{If AR} \neq 0;\ 0.00018 = \frac{0.143\ \mu g/g\ DW \times 0.05}{40\ \mu g/g\ DW}$$

E. **Effect on Humans**

1. **Index of Human Cancer Risk Resulting from Plant Consumption (Index 9)**

a. **Formula**

$$\text{Index 9} = \frac{(I_5 \times DT) + DI}{RSI}$$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
DT = Daily human dietary intake of affected plant tissue (g/day DW)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)**

$$2259.4 = \frac{(0.18\ \mu g/g\ DW \times 74.5\ g/day) + 0.29\ \mu g/day}{0.00607\ \mu g/day}$$

2. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)**

a. **Formula**

$$\text{Index 10} = \frac{(I_5 \times UA \times DA) + DI}{RSI}$$

where:

I_5 = Index 5 = Concentration of pollutant in plant grown in sludge-amended soil (μg/g DW)
UA = Uptake factor of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW]$^{-1}$)
DA = Daily human dietary intake of affected animal tissue (g/day DW) (milk products and meat, poultry, eggs, fish)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation** - Values were not calculated due to lack of data.

3. **Index of Human Cancer Risk Resulting from Consumption of Animal Products Derived from Animals Ingesting Soil (Index 11)**

a. **Formula**

$$\text{If AR} = 0;\ \text{Index 11} = \frac{(BS \times GS \times UA \times DA) + DI}{RSI}$$

$$\text{If AR} \neq 0;\ \text{Index 11} = \frac{(SC \times GS \times UA \times DA) + DI}{RSI}$$

where:

AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
SC = Sludge concentration of pollutant (μg/g DW)
GS = Fraction of animal diet assumed to be soil
UA = Uptake factor of pollutant in animal tissue (μg/g tissue DW [μg/g feed DW]$^{-1}$)
DA = Daily human dietary intake of affected animal tissue (g/day DW) (milk products and meat only)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

4. **Index of Human Cancer Risk Resulting from Soil Ingestion (Index 12)**

a. **Formula**

$$\text{Index 12} = \frac{(I_1 \times DS) + DI}{RSI}$$

where:

I_1 = Index 1 = Concentration of pollutant in sludge-amended soil (μg/g DW)
DS = Assumed amount of soil in human diet (g/day)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific intake (μg/day)

b. **Sample calculation**

$$130 = \frac{(0.100 \ \mu g/g \ DW \times 5 \ g/day) + 0.29 \ \mu g/day}{0.00607 \ \mu g/day}$$

5. **Index of Aggregate Human Cancer Risk (Index 13)**

a. **Formula**

$$\text{Index 13} = I_9 + I_{10} + I_{11} + I_{12} - \left(\frac{3DI}{RSI}\right)$$

where:

I_9 = Index 9 = Index of human cancer risk resulting from plant consumption (unitless)
I_{10} = Index 10 = Index of human cancer risk resulting from consumption of animal products derived from animals feeding on plants (unitless)
I_{11} = Index 11 = Index of human cancer risk resulting from consumption of animal products derived from animals ingesting soil (unitless)
I_{12} = Index 12 = Index of human cancer risk resulting from soil ingestion (unitless)
DI = Average daily human dietary intake of pollutant (μg/day)
RSI = Cancer risk-specific level (μg/day)

b. **Sample calculation (toddler)** - Values were not calculated due to lack of data.

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

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

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:

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

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

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

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

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)

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

Q = Leachate generation rate (m/year)

Θ = Volumetric water content (unitless)

$R = 1 + \frac{P_{dry}}{\Theta} \times K_d$ = 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)

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

K = Hydraulic conductivity of the aquifer (m/day)

i = Average hydraulic gradient between landfill and well (unitless)

$\emptyset$ = Porosity (unitless)

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

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

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)
Ø = Aquifer porosity (unitless)
B = Thickness of saturated zone (m) where:

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

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:

$$t_o = [\ {}_0\int^{\infty} C\ dt] \div C_u$$

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

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**

1.34×10^{-4} μg/L = 1.34×10^{-4} 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

$$145 = \frac{(1.34 \times 10^{-4}\ \mu g/L \times 2\ L/day) + 0.88\ \mu g/day}{0.00607\ \mu g/day}$$

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

$$1.036 = [(2.78 \times 10^{-7}\ hr/sec \times g/mg \times 2660\ kg/hr\ DW \times 0.143\ mg/kg\ DW \times 0.05 \times 3.4\ \mu g/m^3) + 0.0005\ \mu g/m^3] \div 0.0005\ \mu g/m^3$$

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

$$0.639 = \frac{[(1.036 - 1) \times 0.0005\ \mu g/m^3] + 0.0005\ \mu g/m^3}{0.00081\ \mu g/m^3}$$

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

$$0.00029\ \mu g/L = \frac{0.143\ mg/kg\ DW \times 1600000\ kg\ WW \times 0.04\ kg\ DW/kg\ WW \times 10^3\ \mu g/mg}{200\ m \times 20\ m \times 8000\ m \times 10^3\ L/m^3}$$

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

$$0.000078\ \mu g/L = \frac{825000\ \text{kg DW/day} \times 0.143\ \text{mg/kg DW} \times 10^3\ \mu g/mg}{9500\ \text{m/day} \times 20\ \text{m} \times 8000\ \text{m} \times 10^3\ L/m^3}$$

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

$$0.00000095 = \frac{0.00029\ \mu g/L}{300\ \mu g/L}$$

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

$$144.9 = \frac{(0.000078\ \mu g/L \times 11100\ L/kg \times 10^{-3}\ kg/g \times 0.000021 \times 14.3\ g\ WW/day) + 0.88\ \mu g/day}{0.00607\ \mu g/day}$$

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)	0.143	1.937	0.143	0.143	0.143	0.143	1.937	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, ∅ (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)	[35.8]	[484]	[35.8]	[35.8]	[35.8]	[35.8]	[484]	N
Peak concentration, C_u (μg/L)	[4.64×10^{-4}]	[6.28×10^{-3}]	[3.87×10^{-2}]	[35.8]	[4.64×10^{-4}]	[4.64×10^{-4}]	[484]	N
Pulse duration, t_o (years)	[13700]	[13700]	[392]	[5.00]	[13700]	[13700]	[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)	[4.64×10^{-4}]	[6.28×10^{-3}]	[3.87×10^{-2}]	[35.8]	[4.64×10^{-4}]	[4.64×10^{-4}]	[484]	N
Saturated zone assessment (Equations 1 and 3)								
Maximum well concentration, C_{max} (μg/L)	[1.34×10^{-4}]	[1.82×10^{-3}]	[3.30×10^{-4}]	[3.89×10^{-3}]	[4.30×10^{-4}]	[4.64×10^{-4}]	[11.2]	N
Index of groundwater concentration resulting from landfilled sludge, Index 1 (μg/L) (Equation 4)	[1.34×10^{-4}]	[1.82×10^{-3}]	[3.30×10^{-4}]	[3.89×10^{-3}]	[4.30×10^{-4}]	[4.64×10^{-4}]	[11.2]	0
Index of human toxicity/cancer risk resulting from groundwater contamination, Index 2 (unitless) (Equation 5)	[145]	[146]	[145]	[146]	[145]	[145]	[3840]	[145]

[a]N = Null condition, where no landfill exists; no value is used.
[b]NA = Not applicable for this condition.

BENZO(A)PYRENE

p. 3-2 should read:

Index 1 Values

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
	Typical	0.01	0.01	0.013	0.01
	Worst	0.01	0.014	0.057	0.015

p. 3-5 should read:

Index 5 Values (ug/g DW)

Diet	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Animal	Typical	0.0042	0.0043	0.0056	0.0043
	Worst	0.0042	0.0062	0.024	0.0063
Human	Typical	0.018	0.019	0.023	0.019
	Worst	0.018	0.026	0.1	0.027

p. 3-7 should read:

Index 7 Values

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
	Typical	0.00011	0.00011	0.00014	0.00011
	Worst	0.00011	0.00016	0.0006	0.00016

p. 3-11 should read:

Index 9 Values

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	48	55	120	55
	Worst	48	150	1100	160
Adult	Typical	140	170	340	170
	Worst	140	440	3000	440

p. 3-16 should read:

Index 12 values

Group	Sludge Concentration	Sludge Application Rate (mt/ha) 0	5	50	500
Toddler	Typical	60	56	59	56
	Worst	60	56	95	60
Adult	Typical	150	150	150	150
	Worst	150	150	150	150

p. 3-2 Index 1 Values

Preliminary Conclusion - should read:

Landspreading of sludge may slightly increase the soil concentration of BaP when sludge containing a typical concentration of BaP is applied at the 50 mt/ha rate and when sludge containing a high concentration of BaP is applied at the 5, 50, and 500 mt/ha rates.

p. 3-5 Index 5 Values

Preliminary Conclusion - should read:

Landspreading of sludge containing a worst concentration of BaP is expected to increase the tissue concentration of BaP in plants in the animal and human diet slightly at the 5 and 500 mt/ha application rates and significantly at the 50 mt/ha application rate.

p. 3-11 Index 9 Values

Preliminary Conclusion - should read:

Landspreading of sludge containing BaP is expected to increase the risk of cancer for adults or toddlers who consume plants grown on the sludge-amended soil when applied at any application rate (5 to 500 mt/ha) at either typical or worst concentrations.