Water                                                                                          June, 1985
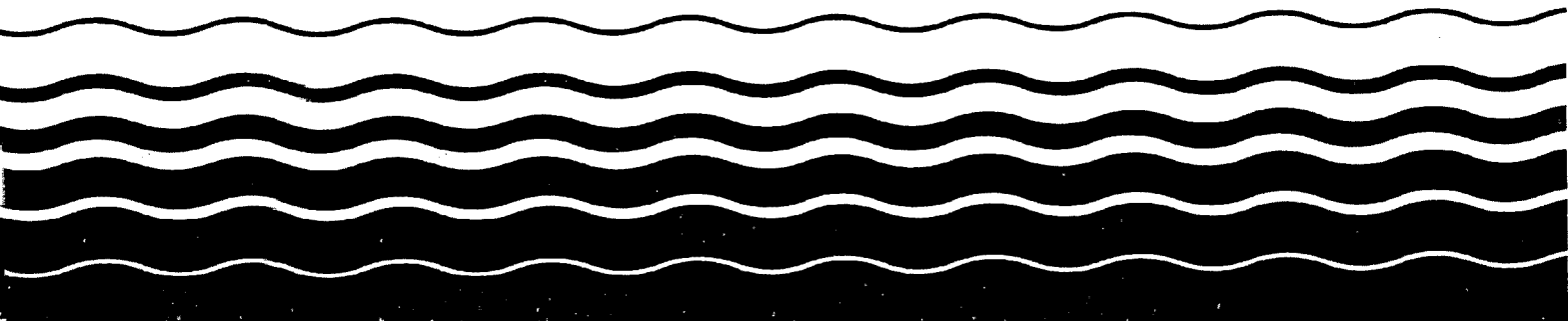
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# Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Benzene

# 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.

# TABLE OF CONTENTS

# TABLE OF CONTENTS
## (Continued)

# 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. Benzene was initially identified as being of potential concern when sludge is placed in a landfill or incinerated.* This profile is a compilation of information that may be useful in determining whether benzene poses an actual hazard to human health or the environment when sludge is disposed of by these methods.

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

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

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

The preliminary hazard indices for selected exposure routes pertinent to landfilling and incineration 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 BENZENE IN MUNICIPAL SEWAGE SLUDGE

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

### I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

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

### II. LANDFILLING

Disposal of sludge in a landfill may be expected to result in groundwater concentrations of benzene in the part-per-trillion range for all scenarios, except possibly when all worst-case parameters occur. When all worst-case parameters occur, a groundwater concentration of benzene in the part-per-billion range may be expected (see Index 1).

Landfilling of sludge is not expected to result in an increase in potential cancer risk to humans, except possibly when all worst-case parameters occur (see Index 2).

### III. INCINERATION

Incineration of sludge is not expected to result in benzene concentrations in air that exceed background levels (see Index 1). Sludge incineration is not expected to increase the potential cancer risk to humans due to benzene (see Index 2).

### IV. OCEAN DISPOSAL

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

PRELIMINARY HAZARD INDICES FOR BENZENE
IN MUNICIPAL SEWAGE SLUDGE

## I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

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

## II. LANDFILLING

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

    1.  Explanation - Calculates groundwater contamination which
        could occur in a potable aquifer in the landfill vicin-
        ity. Uses U.S. EPA's Exposure Assessment Group (EAG)
        model, "Rapid Assessment of Potential Groundwater Contam-
        ination Under Emergency Response Conditions" (U.S. EPA,
        1983a). Treats landfill leachate as a pulse input, i.e.,
        the application of a constant source concentration for a
        short time period relative to the time frame of the anal-
        ysis. In order to predict pollutant movement in soils
        and groundwater, parameters regarding transport and fate,
        and boundary or source conditions are evaluated. Trans-
        port 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 concentra-
        tions. This partition coefficient, along with soil bulk
        density and volumetric water content, are used to calcu-
        late the retardation factor. A computer program (in
        FORTRAN) was developed to facilitate computation of the
        analytical solution. The program predicts pollutant con-
        centration as a function of time and location in both the
        unsaturated and saturated zone. Separate computations
        and parameter estimates are required for each zone. The
        prediction requires evaluations of four dimensionless
        input values and subsequent evaluation of the result,
        through use of the computer program.

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

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

## 3. Data Used and Rationale

### a. Unsaturated zone

#### i. Soil type and characteristics

##### (a) Soil type

| | |
|---|---|
| Typical | Sandy loam |
| Worst | Sandy |

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

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

| | |
|---|---|
| Typical | 1.53 g/mL |
| Worst | 1.925 g/mL |

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

##### (c) Volumetric water content ($\theta$)

| | |
|---|---|
| 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, 1984.

**(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 ($\alpha$)

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       0.326 mg/kg DW
Worst         6.58  mg/kg DW

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

### (b) Degradation rate ($\mu$) = 0.0107 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:

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

(U.S. EPA 1984b) (See Section 4, p. 4-2.)

(c) **Organic carbon partition coefficient ($K_{oc}$) = 74.2 mL/g**

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

Typical    0.44  (unitless)
Worst      0.389 (unitless)

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

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

Typical    0.86 m/day
Worst      4.04 m/day

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

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

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

ii. **Site parameters**

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

Typical     0.001 (unitless)
Worst       0.02  (unitless)

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

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

Typical     100 m
Worst        50 m

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

(c) **Dispersivity coefficient ($\alpha$)**

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 ($\mu$) = 0 day$^{-1}$**

Degradation is assumed not to occur in the saturated zone.

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

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

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

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

6. **Preliminary Conclusion** - Disposal of sludge in a landfill may be expected to result in groundwater concentrations of benzene in the part-per-trillion range for all scenarios, except possibly when all worst-case parameters occur. When all worst-case parameters occur, a groundwater concentration of benzene in the part-per-billion range may be expected.

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. 3-14.

   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) = 342 µg/day**

      The Department of National Health and Welfare of Canada (1979) reported the estimated yearly human intake of benzene for non-occupationally exposed persons to be 125 mg/year or 342 µg/day. The National Cancer Institute (1977) estimated that an individual might ingest as much as 250 µg/day from food (U.S. EPA, 1983b). Estimates of benzene in food (such as eggs = 500 to 1,900 ng/g benzene) may contribute to a relatively high DI when compared to the cancer risk-specific intake (RSI) (see next parameter) (U.S. EPA, 1980b). (See Section 4, pp. 4-3 and 4-4.)

   d. **Cancer potency = $4.5 \times 10^{-2}$ (mg/kg/day)$^{-1}$**

      The cancer potency derived by the U.S. EPA (1984a) was based on data from a study in which oral ingestion of benzene resulted in zymbal gland and mammary cancer in rats. (See Section 4, p. 4-4.)

   e. **Cancer risk-specific intake (RSI) = 1.6 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:

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

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** - Landfilling of sludge is not expected to result in an increase in potential cancer risk to humans, except possibly when all worst-case parameters occur.

## 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, 1984). This model uses the thermodynamic and mass balance relationships appropriate for multiple hearth incinerators to relate the input sludge characteristics to the stack gas parameters. Dilution and dispersion of these stack gas releases were described by the U.S. EPA's Industrial Source Complex Long-Term (ISCLT) dispersion model from which normalized annual ground level concentrations were predicted (U.S. EPA, 1979). The predicted pollutant concentration can then be compared to a ground level concentration used to assess risk.

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

3.  **Data Used and Rationale**

    a.  Coefficient to correct for mass and time units (C) = 2.78 x $10^{-7}$ 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 H2O/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 H2O/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  0.326 mg/kg DW
   Worst    6.58  mg/kg DW

   See Section 3, p. 3-4.

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

   Typical    0.05 (unitless)
   Worst      0.20 (unitless)

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

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

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

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

f. **Background concentration of pollutant in urban
   air (BA) = 14 $\mu$g/m$^3$**

14 $\mu g/m^3$ is the average of air concentrations from three U.S. cities: 5, 18, and 19 $\mu g/m^3$ from Dallas, Chicago, and Los Angeles, respectively (U.S. EPA, 1983b). (See Section 4, p. 4-3.)

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 | 1.0 |
| | Worst | 1.0 | 1.0 | 1.0 |
| Worst | Typical | 1.0 | 1.0 | 1.0 |
| | Worst | 1.0 | 1.0 | 1.0 |

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

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

6. **Preliminary Conclusion** - Incineration of sludge is not expected to result in benzene concentrations in air that exceed background levels.

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. 3-11.

**b. Background concentration of pollutant in urban air (BA) = 14 $\mu g/m^3$**

See Section 3, p. 3-11.

**c. Cancer potency = $2.6 \times 10^{-2}$ (mg/kg/day)$^{-1}$**

Occupational exposure by inhalation has resulted in leukemia in humans. A potency value of $5.2 \times 10^{-2}$ (mg/kg/day)$^{-1}$, cited by U.S. EPA (1984a), included an assumed absorption factor of 0.5, making this latter value applicable to absorbed dose rather than inhaled dose. To assess inhaled dose, the absorption factor has been removed, resulting in a value of $2.6 \times 10^{-2}$ (mg/kg/day)$^{-1}$. (See Section 4, p. 4-5.)

**d. Exposure criterion (EC) = 0.13 $\mu g/m^3$**

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 | 110 | 110 | 110 |
| | Worst | 110 | 110 | 110 |
| Worst | Typical | 110 | 110 | 110 |
| | Worst | 110 | 110 | 110 |

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

5. **Value Interpretation** — Value > 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** — Sludge incineration is not expected to increase the potential cancer risk to humans due to benzene.

## IV. OCEAN DISPOSAL

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

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

| Site Characteristics | Condition of Analysis[a,b,c] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Sludge concentration | T | W | T | T | T | T | W | N |
| **Unsaturated Zone** | | | | | | | | |
| Soil type and characteristics[d] | T | T | W | NA | T | T | NA | N |
| Site parameters[e] | T | T | T | W | T | T | W | N |
| **Saturated Zone** | | | | | | | | |
| Soil type and characteristics[f] | T | T | T | T | W | T | W | N |
| Site parameters[g] | T | T | T | T | T | W | W | N |
| Index 1 Value ($\mu$g/L) | $2.6 \times 10^{-4}$ | $5.3 \times 10^{-3}$ | $6.7 \times 10^{-4}$ | $8.9 \times 10^{-3}$ | $1.4 \times 10^{-3}$ | $1.0 \times 10^{-2}$ | 38 | 0 |
| Index 2 Value | 210 | 210 | 210 | 210 | 210 | 210 | 260 | 210 |

[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 ($\theta$), and fraction of organic carbon ($f_{oc}$).
[e]Leachate generation rate (Q), depth to groundwater (h), and dispersivity coefficient ($\alpha$).
[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 ($\alpha$).

PRELIMINARY DATA PROFILE FOR BENZENE IN MUNICIPAL SEWAGE SLUDGE

Benzene is produced principally from coal tar distillation, from petroleum catalytic reforming of light naphthas, and in coal processing and coal coking operations. It is used as an intermediate for the synthesis of chemicals in the chemical and pharmaceutical industries, a thinner for lacquer, a degreasing and cleaning agent, a solvent in the rubber industry, an antiknock fuel additive, a general solvent in laboratories, and in the preparation and use of inks in the graphic arts industry.

I. OCCURRENCE

  A. Sludge

    1. Frequency of Detection

| | |
|---|---|
| Detected in 264 of 436 samples (61%) from 40 POTWs | U.S. EPA, 1982 (p. 41) |
| Detected in 27 of 41 samples (66%) from 10 POTWs | U.S. EPA, 1982 (p. 49) |

    2. Concentration

| | |
|---|---|
| 1 to 953 µg/L from 40 POTWs<br>1 to 934 µg/L from 10 POTWs | U.S. EPA, 1982 (p. 41,49) |
| Typical (median) 0.326 mg/kg DW<br>Worst (95th percentile) 6.58 mg/kg DW | Values statistically derived from sludge concentration data presented in U.S. EPA, 1982 |

  B. Soil - Unpolluted

    1. Frequency of Detection

      Data not immediately available.

    2. Concentration

| | |
|---|---|
| Considering the solubility and volatility of benzene, it can be concluded that benzene may not persist in soil, and volatilization and washout by rain may be important processes for the removal of benzene from soil. | U.S. EPA, 1983b (p. 5) |

| | |
|---|---|
| The degradation rate of benzene, $0.0107$ (day)$^{-1}$ was derived by the U.S. EPA (1984b). | U.S. EPA, 1984b |

## C. Water - Unpolluted

### 1. Frequency of Detection

| | |
|---|---|
| 4 of 10 water supplies surveyed using volatile organic analysis contained benzene. | U.S. EPA, 1980b (p. C-1) |

### 2. Concentration

#### a. Freshwater

| | |
|---|---|
| 3100 µg/L 24-hour average, 7000 µg/L ceiling, freshwater aquatic life water quality criterion | U.S. EPA, 1980a (p. 19) |

#### b. Seawater

| | |
|---|---|
| 920 µg/L 24-hour average, 2100 µg/L ceiling, saltwater aquatic life water quality criterion | U.S. EPA, 1980a (p. 19) |

#### c. Drinking Water

| | |
|---|---|
| 0.1 to 0.3 µg/L from water supplies of 4 U.S. cities | U.S. EPA, 1983b (p. 6) |
| 10 µg/L highest concentration observed in finished water | U.S. EPA, 1980b |

#### d. Groundwater

| | |
|---|---|
| Coniglio et al. (1980) reported only 8.5% frequency of occurrence of benzene in groundwater samples throughout the United States. | U.S. EPA, 1984a (p. 1) |

## D. Air

### 1. Frequency of Detection

| | |
|---|---|
| Benzene comprises approximately 2.15% (by weight) of the total hydrocarbon emissions from a gasoline engine. | U.S. EPA, 1980b (p. C-8) |

## 2. Concentration

### a. Urban

| | |
|---|---|
| 0.96 to 7.66 mg/m$^3$ in air around gas stations | U.S. EPA, 1980b (p. C-8) |
| 0.048 mg/m$^3$ average, 0.182 mg/m$^3$ maximum in Los Angeles air | U.S. EPA, 1980b (p. C-8) |
| 5 µg/m$^3$ in Dallas air<br>18 µg/m$^3$ in Chicago air<br>19 µg/m$^3$ in Los Angeles air | U.S. EPA, 1983b (p. 6) |

### b. Rural

| | |
|---|---|
| 0.054 µg/m$^3$ rural background level | U.S. EPA, 1983b (p. C-8) |

## E. Food

### 1. Total Average Intake

| | |
|---|---|
| Benzene has been detected in various food categories such as fruits, nuts, vegetables dairy products, meat, fish, poultry, eggs, and several beverages. The National Cancer Institute estimated that an individual might ingest as much as 250 µg/day of benzene from these sources. | U.S. EPA, 1983b (p. 6) |
| The estimated yearly human intake of benzene for those non-occupationally exposed is 125 mg/year. | Dept. National Health and Welfare of Canada, 1979 (p. 57) |

### 2. Concentration

| | |
|---|---|
| The U.S. EPA estimated the weight average bioconcentration factor of benzene for the edible portion of shellfish and fish consumed by Americans to be 5.21. | U.S. EPA, 1983b (p. C-7) |
| The exposure to benzene through general dietary intake is not considered a problem for the general population. | U.S. EPA, 1980b (p. C-4) |

Estimated benzene level in food:

| Food | Benzene Level (ng/g) |
|---|---|
| Heat treated or canned beef | 2 |
| Jamaican rum | 120 |
| Irradiated beef | 19 |
| Eggs | 500-1,900 |

## II. HUMAN EFFECTS

### A. Ingestion

#### 1. Carcinogenicity

##### a. Qualitative Assessment

There is limited evidence that benzene is carcinogenic in animals by the oral route.

##### b. Potency

Cancer potency = $4.45 \times 10^{-2}$ $(mg/kg/day)^{-1}$ based on a study in which oral ingestion of benzene resulted in zymbal gland and mammary cancer in rats.

##### c. Effects

Data not immediately available.

#### 2. Chronic Toxicity

Data not immediately available.

#### 3. Absorption Factor

Half-life in water 1 to 6 days, estimated from reaeration rate of 0.574 and the oxygen reaeration rate of 0.19 $day^{-1}$ to 0.96 $day^{-1}$.

#### 4. Existing Regulations

No standard for benzene in water exists, but Cleland and Kingsburg (1977), using several assumptions and ACGIH air standards, have suggested values of 1071

and 414 µg/L for ingested water, and
107 µg/L for ingested water, based on
the potential carcinogenicity of benzene.

B.  Inhalation

1.  Carcinogenicity

a.  Qualitative Assessment

There is sufficient evidence that
benzene is carcinogenic to humans --
by inhalation.

| | |
|---|---|
| Gerard and Revol (1970) and Gerard et al. (1968) reported a significant association between benzene exposure and acute myeloblastic leukemia in human epidemiologic studies. | U.S. EPA, 1983b (p. 11) |

b.  Potency

| | |
|---|---|
| Cancer potency = $2.6 \times 10^{-2}$ $(mg/kg/day)^{-1}$. A potency value of $5.2 \times 10^{-2}$ $(mg/kg/day)^{-1}$ cited in U.S. EPA, 1984a, included an assumed absorption factor of 0.5, making the latter value applicable to absorbed dose rather than inhaled dose. To assess inhaled dose, the absorption factor has been removed resulting in a value of $2.6 \times 10^{-2}$ $(mg/kg/day)^{-1}$. | U.S. EPA, 1984a (p. 22) |

c.  Effects

| | |
|---|---|
| Occupational exposure by inhalation has resulted in leukemia in humans. | U.S. EPA, 1984a (p. 22) |

2.  Chronic Toxicity

a.  Inhalation Threshold or MPIH

Data not presented since cancer
potency is used to assess hazard.

b.  Effects

| | |
|---|---|
| Pancytopenia, impairment of immunological system. | U.S. EPA, 1983b (p. 15) |

3.  Absorption Factor

| | |
|---|---|
| 40 to 50 % retained at exposure to < 110 ppm | U.S. EPA, 1983b (p. 8) |

28 to 34% absorption on exposure to
6000 ppm

4. **Existing Regulations**

25 ppm (80 mg/m$^3$) ACGIH (1979)           U.S. EPA, 1980b
                                            (p. C-61)
10 ppm (30 mg/m$^3$) ACGIH (1980)           U.S. EPA, 1983b
                                            (p. 20)

## III. PLANT EFFECTS

Data not immediately available.

## IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

A. **Toxicity**

See Table 4-1.

Benzene is biologically converted to phenol     U.S. EPA, 1980b
as well as catechol and hydroquenone.           (p. C-10)

B. **Uptake**

Data not immediately available.

## V. AQUATIC LIFE EFFECTS

A. **Toxicity**

1. **Freshwater**

a. **Acute**

5300 µg/L                                  U.S. EPA, 1980b
                                            (p. vi)
3100 µg/L proposed criteria                U.S. EPA, 1980a
24-hr average                              (p. 19)
7000 µg/L ceiling level
9.5 µg/L in freshwater for sockeye          U.S. EPA, 1983b
salmon

b. **Chronic**

Data not immediately available.

2. **Saltwater**

a. **Acute**

5100 µg/L                                  U.S. EPA, 1980b
                                            (p. vi)

|  |  |
|---|---|
| 920 µg/L 24-hr average proposed criteria | U.S. EPA, 1980a (p. 19) |
| 2100 µg/L ceiling level | |
| 4.9 µg/L in saltwater for sockeye salmon | U.S. EPA, 1983b (p. 20) |

### b. Chronic

|  |  |
|---|---|
| 700 µg/L resulted in adverse effects on fish exposed 168 days. | U.S. EPA, 1980b (p. vi) |

## B. Uptake

|  |  |
|---|---|
| The weighted average bioconcentration factor for benzene and the edible portion of all freshwater and estuarine aquatic organisms consumed by Americans is calculated to be 5.21. | U.S. EPA, 1980b (p. C-7) |

## VI. SOIL BIOTA EFFECTS

|  |  |
|---|---|
| Benzene can be degraded by a number of micro-organisms. In some instances the organism can use benzene as a source of energy and carbon. | U.S. EPA, 1983b (p. 3) |

## VII. PHYSICOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

|  |  |
|---|---|
| Molecular weight: 78.12 | U.S. EPA, 1983b (p. 1) |

Volatile, colorless, liquid hydrocarbon
Boiling point: 80.1°C
Melting point: 5.5°C
Water solubility: 1780 mg/L at 25°C
Density: 0.87865 g/mL at 20°C

|  |  |
|---|---|
| 4.8 hour volatilization half-life in 1 meter water column at 25°C | U.S. EPA, 1983b (p. 3) |
| Based on an organic content of 2.6%, the Freudlich adsorption constant for a silty clay loam has been determined to be 2.4. | U.S. EPA, 1983b (p. 5) |
| Organic carbon partition coefficient ($K_{oc}$) = 74.2 mL/g | Estimated from Lyman, 1982 |

TABLE 4-1. TOXICITY OF BENZENE TO DOMESTIC ANIMALS AND WILDLIFE

| Species (N)[a] | Chemical Form Administered | Feed Concentration (μg/g DW) | Water Concentration (mg/L) | Daily Intake (mg/kg DW) | Duration of Study | Effects | References |
|---|---|---|---|---|---|---|---|
| Rat (30/sex) | Benzene in gavage | NR[b] | NR | 50 | 52 weeks | Control: 1/30 male, 1/30 female developed leukemia; 0/30 male, 0/30 female developed zymbal gland carcinoma and skin carcinoma<br><br>50 mg/kg group: 2/30 male, 2/30 female developed leukemia; 0/30 male, 2/30 female developed zymbal gland carcinoma | U.S. EPA, 1983b (p. 10) |
| Rat (35/sex) | Benzene in gavage | NR | NR | 250 | 50 weeks | Control: see above 250 mg/kg group: 4/35 male, 1/35 female developed leukemia; 8/35 female, 0/35 male developed zymbal gland carcinoma; 2/35 female, 0/35 male developed skin carcinoma | U.S. EPA, 1983b (p. 10) |
| Mice | Benzene in gavage | NR | NR | 0.3-1 | Days 6 to 15 of gestation | Maternal toxicity and embryonic reabsorption but no malformations | U.S. EPA, 1983b (p. 14) |

[a]N = Number of experimental animals when reported.
[b]NR = Not reported.

4-8

# SECTION 5

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APPENDIX

## PRELIMINARY HAZARD INDEX CALCULATIONS FOR BENZENE IN MUNICIPAL SEWAGE SLUDGE

### I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

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

### II. LANDFILLING

#### A. Procedure

Using Equation 1, several values of $C/C_0$ 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, $t_0$, 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, $C_0$, 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

$$\frac{C(\chi,t)}{C_0} = \frac{1}{2} \left[ \exp(A_1) \, \text{erfc}(A_2) + \exp(B_1) \, \text{erfc}(B_2) \right] = P(\chi,t)$$

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

where:

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

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

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

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

and where for the unsaturated zone:

$C_0$ = SC x CF = Initial leachate concentration ($\mu$g/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)
$\chi$ = h = Depth to groundwater (m)
$D^*$ = $\alpha$ x $V^*$ (m$^2$/year)
$\alpha$ = Dispersivity coefficient (m)

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

Q = Leachate generation rate (m/year)
$\Theta$ = Volumetric water content (unitless)

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

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

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

$\mu$ = Degradation rate (day$^{-1}$)

and where for the saturated zone:

$C_0$ = Initial concentration of pollutant in aquifer as determined by Equation 2 ($\mu$g/L)
t = Time (years)
$\chi$ = $\Delta\ell$ = Distance from well to landfill (m)
$D^*$ = $\alpha$ x $V^*$ (m$^2$/year)
$\alpha$ = Dispersivity coefficient (m)

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

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

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

$\emptyset$ = Aquifer porosity (unitless)

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

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

## C. Equation 2. Linkage Assessment

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

where:

$C_o$ = Initial concentration of pollutant in the saturated zone as determined by Equation 1 ($\mu$g/L)

$C_u$ = Maximum pulse concentration from the unsaturated zone ($\mu$g/L)

Q = Leachate generation rate (m/year)

W = Width of landfill (m)

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

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

$\emptyset$ = Aquifer porosity (unitless)

B = Thickness of saturated zone (m) where:

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

## 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 ($\chi$ = h) as determined by the following equation:

$$t_o = [\int_0^\infty C \, dt] \div C_u$$

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

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

   1. **Formula**

   $$\text{Index } 1 = C_{max}$$

   where:

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

   2. **Sample Calculation**

   $$2.621 \times 10^{-4} \ \mu g/L = 2.621 \times 10^{-4} \ \mu g/L$$

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 ($\mu g/L$)
   $AC$ = Average human consumption of drinking water (L/day)
   $DI$ = Average daily human dietary intake of pollutant ($\mu g/day$)
   $RSI$ = Cancer risk-specific intake ($\mu g/day$)

   2. **Sample Calculation**

   $$213.8 = \frac{(2.621 \times 10^{-4} \ \mu g/L \times 2 \ L/day) + 342 \ \mu g/day}{1.6 \ \mu g/day}$$

## 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

$$1.000 = [(2.78 \times 10^{-7} \text{ hr/sec} \times \text{g/mg} \times 2660 \text{ kg/hr DW} \times 0.326 \text{ mg/kg DW}$$

$$\times \; 0.05 \times 3.4 \; \mu g/m^3) + 14 \; \mu g/m^3] \div 14 \; \mu g/m^3$$

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

$$107.7 = \frac{[(1.000 - 1) \times 14 \; \mu g/m^3] + 14 \; \mu g/m^3}{0.13 \; \mu g/m^3}$$

IV. **OCEAN DISPOSAL**

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

# 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) | 0.326 | 6.58 | 0.326 | 0.326 | 0.326 | 0.326 | 6.58 | 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, $\theta$ (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, $\alpha$ (m) | 0.5 | 0.5 | 0.5 | NA | 0.5 | 0.5 | NA | N |
| **Saturated zone** | | | | | | | | |
| Soil type and characteristics | | | | | | | | |
| Aquifer porosity, $\phi$ (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, $\Delta\ell$ (m) | 100 | 100 | 100 | 100 | 100 | 50 | 50 | N |
| Dispersivity coefficient, $\alpha$ (m) | 10 | 10 | 10 | 10 | 10 | 5 | 5 | N |

| 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) | 81.5 | 1650 | 81.5 | 81.5 | 81.5 | 81.5 | 1645 | N |
| Peak concentration, $C_u$ (µg/L) | 2.392 | 48.28 | 6.172 | 81.5 | 2.392 | 2.392 | 1645 | N |
| Pulse duration, $t_o$ (years) | 5.040 | 5.040 | 5.000 | 5.000 | 5.040 | 5.040 | 5.000 | 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) | 2.39 | 48.3 | 6.17 | 81.5 | 2.39 | 2.39 | 1650 | N |
| Saturated zone assessment (Equations 1 and 3) | | | | | | | | |
| Maximum well concentration, $C_{max}$ (µg/L) | 0.0002621 | 0.005292 | 0.0006711 | 0.008862 | 0.001393 | 0.01049 | 38.07 | N |
| Index of groundwater concentration resulting from landfilled sludge, Index 1 (µg/L) (Equation 4) | 0.0002621 | 0.005292 | 0.0006711 | 0.008862 | 0.001393 | 0.01049 | 38.07 | 0 |
| Index of human cancer risk resulting from groundwater contamination, Index 2 (unitless) (Equation 5) | 213.8 | 213.8 | 213.8 | 213.8 | 213.8 | 213.8 | 261.3 | 213.8 |

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