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# Environmental Profiles and Hazard Indices for Constituents of Municipal Sludge: Nickel

## 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. Nickel (Ni) was initially identified as being of potential concern when sludge is landspread (including distribution and marketing), placed in a landfill, or incinerated.* This profile is a compilation of information that may be useful in determining whether Ni 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 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 NICKEL 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 Nickel

Landspreading of sludge may result in increased soil concentrations of Ni when sludge with a typical concentration of Ni is applied at a high rate (500 mt/ha) or when sludge with a high (worst) concentration of Ni is applied at any rate (5 to 500 mt/ha) (see Index 1).

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

The toxic hazard to soil biota posed by increased concentrations of Ni in sludge-amended soil could not be evaluated due to lack of data (see Index 2). Landspreading of sludge is not expected to result in Ni concentrations in soil biota that pose a toxic hazard to their predators (see Index 3).

#### C. Effect on Plants and Plant Tissue Concentration

Landspreading of sludge is not expected to result in soil concentrations of Ni that exceed phytotoxic concentrations for plants except possibly when sludge containing a high concentration of Ni is applied at a high rate (500 mt/ha) (see Index 4). Concentrations of Ni in plant tissues may increase above background concentrations when sludge is landspread, except possibly for plants serving as animal feed when typical sludge is applied at low rates (5 and 50 mt/ha) (see Index 5). The increased plant tissue concentrations of Ni expected to result from landspreading of sludge may be precluded by phytotoxicity for plants in the human diet when sludge containing a high concentration of Ni is applied at a high rate (500 mt/ha) (see Index 6).

#### D. Effect on Herbivorous Animals

Landspreading of sludge is not expected to result in plant tissue concentrations of Ni that pose a toxic hazard to herbivorous animals (see Index 7). Landspreading of sludge is not expected to result in a toxic hazard due to Ni for grazing animals that inadvertently ingest sludge-amended soil (see Index 8).

### E. Effect on Humans

The consumption of plants grown on sludge-amended soil by humans is not expected to pose a toxic threat except possibly for adults when high-Ni sludge is applied at high rates (50 and 500 mt/ha) and for toddlers when high-Ni sludge is applied at a high rate (500 mt/ha). However, the plant concentrations of Ni which are toxic to humans may be precluded by phytotoxicity when high-Ni sludge is applied at a high rate (500 mt/ha) (see Index 9). Landspreading of sludge is not expected to pose a health hazard due to Ni for humans who consume animal products derived from animals that feed on plants grown in sludge-amended soil (see Index 10); who consume animal products derived from animals that inadvertently ingest sludge-amended soil (see Index 11); or who ingest sludge or sludge-amended soil (see Index 12). The aggregate amount of Ni in the human diet resulting from landspreading of sludge is not expected to pose a health hazard except possibly for toddlers when high-Ni sludge is applied at a high rate (500 mt/ha) and for adults when high-Ni sludge is applied at high rates (50 and 500 mt/ha). However, the aggregate health hazard expected for toddlers and adults when high-Ni sludge is applied at a high rate may be lower since consumption of plants grown in sludge-amended soil may be limited by phytotoxicity (see Index 13).

## II. LANDFILLING

Landfilling of sludge may increase Ni concentrations in groundwater at the well above background concentrations; this increase may be large when all worst-case conditions prevail at a disposal site (see Index 1). Landfilling of sludge is not expected to pose a human health threat due to Ni from groundwater contamination except possibly when all worst-case conditions prevail at a disposal site (see Index 2).

## III. INCINERATION

Incineration of sludge may increase air concentrations of Ni above background concentrations (see Index 1). Incineration of sludge may slightly increase the human cancer risk due to inhalation of Ni above the risk posed by background urban air concentrations of Ni. An increase may not occur when sludge containing a typical concentration of Ni is incinerated at a low feed rate (2660 kg/hr DW) and a typical fraction of Ni is emitted through the stack (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.

## SECTION 3

## PRELIMINARY HAZARD INDICES FOR NICKEL IN MUNICIPAL SEWAGE SLUDGE

I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

A. Effect on Soil Concentration of Nickel

1. Index of Soil Concentration Increment (Index 1)

a. **Explanation** - Shows degree of elevation of pollutant concentration in soil to which sludge is applied. Calculated for sludges with typical (median if available) and worst (95th percentile if available) pollutant concentrations, respectively, for each of four sludge loadings. Applications (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 application as may be used on public lands, reclaimed areas or home gardens.

500 mt/ha Cumulative loading after years of application.

b. **Assumptions/Limitations** - Assumes pollutant is distributed and retained within the upper 15 cm of soil (i.e., the plow layer), which has an approximate mass (dry matter) of $2 \times 10^3$ mt/ha.

c. **Data Used and Rationale**

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

Typical 44.7 µg/g DW
Worst 662.7 µg/g DW

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

ii. **Background concentration of pollutant in soil (BS)** = 18.6 μg/g DW

The value is the median level of Ni for U.S. cropland soils which are shown to range between 0.6 and 269 μg/g of soil (Holmgren et al., 1983). (See Section 4, p. 4-1.)

d. **Index 1 Values**

| Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|
| Typical | 1.0 | 1.0 | 1.0 | 1.3 |
| Worst | 1.0 | 1.1 | 1.8 | 7.9 |

e. **Value Interpretation** - Value equals factor by which expected soil concentration exceeds background when sludge is applied. (A value of 2 indicates concentration is doubled; a value of 0.5 indicates reduction by one-half.)

f. **Preliminary Conclusion** - Landspreading of sludge may result in increased soil concentrations of Ni when sludge with a typical concentration of Ni is applied at a high rate (500 mt/ha) or when sludge with a high (worst) concentration of Ni is applied at any rate (5 to 500 mt/ha).

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 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. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 18.6 μg/g DW

See Section 3, p. 3-2.

iii. **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. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS)** = 18.6 μg/g DW

See Section 3, p. 3-2.

iii. **Uptake slope of pollutant in soil biota (UB)** = 1.17 μg/g tissue DW $(\mu g/g \text{ soil DW})^{-1}$

The only available slope was for earthworms. The value selected for the slope is the mean for two locations where Ni content in the soil and in earthworms was examined at varying distances from a roadway (Gish and Christensen, 1973). (See Section 4, p. 4-22.)

iv. **Background concentration in soil biota (BB) =** 13 μg/g DW

The background value is for earthworms and is the mean for earthworms obtained from normal soil (Gish and Christensen, 1973). (See Section 4, p. 4-22.)

v. **Feed concentration toxic to predator (TR) =** 300 μg/g DW

Using birds as a model earthworm predator, it was desired to choose the most sensitive bird species. National Academy of Science (NAS) (1980) suggested as a maximum tolerable level in poultry feed of 300 mg/kg DW, based on findings of decreased growth in chickens at 500 mg, added to the diet as $NiSO_4$ or Ni acetate (Weber and Reid, 1968). (See Section 4, p. 4-17.)

d. **Index 3 Values**

| Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|
| Typical | 0.043 | 0.044 | 0.046 | 0.064 |
| Worst | 0.043 | 0.050 | 0.10 | 0.55 |

e. **Value Interpretation** - Value 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** - Landspreading of sludge is not expected to result in Ni concentrations in soil biota that pose a toxic hazard to their predators.

C. **Effect on Plants and Plant Tissue Concentration**

1. **Index of Phytotoxicity (Index 4)**

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

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. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 18.6 μg/g DW**

See Section 3, p. 3-2.

iii. **Soil concentration toxic to plants (TP) = 50 μg/g DW**

In several experiments where unaltered or Ni-enriched sludges were applied to acid soils (pH > 6.5), soil concentrations at which reduced (30 percent or more) yields were observed were about 50 to 80 μg/g (Mitchell et al., 1978; Valdares et al., 1983; Weber, 1972). In neutral soils, threshold values tended to be much higher, in the range of 200 to 300 μg/g; the choice of 50 μg/g, then, is conservative. (See Section 4, pp. 4-8 to 4-11.)

d. **Index 4 Values**

| Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|
| Typical | 0.37 | 0.37 | 0.38 | 0.48 |
| Worst | 0.37 | 0.40 | 0.69 | 2.9 |

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

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to result in soil concentrations of Ni that exceed phytotoxic concentrations for plants except possibly when sludge containing a high concentration of Ni is applied at a high rate (500 mt/ha).

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

a. **Explanation** - Calculates expected tissue concentration increment 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 a linear uptake slope. Neglects the effect of time; i.e., cumulative loading over several years is treated equivalently to single application of the same amount. 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. **Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

ii. **Background concentration of pollutant in soil (BS) = 18.6 μg/g DW**

See Section 3, p. 3-2.

iii. **Conversion factor between soil concentration and application rate (CO) = 2 kg/ha $(\mu g/g)^{-1}$**

Assumes pollutant is distributed and retained within upper 15 cm of soil (i.e. plow layer) which has an approximate mass (dry matter) of $2 \times 10^3$.

iv. **Uptake slope of pollutant in plant tissue (UP)**

Animal diet:
Rye forage 0.026 μg/g tissue DW $(kg/ha)^{-1}$

Human diet:
Cabbage 0.80 μg/g tissue DW $(kg/ha)^{-1}$

The highest uptake slope obtained in a field study for crops consumed by animals was 0.026 μg/g $(kg/ha)^{-1}$ for rye forage grown at pH 5.0 to 6.0 (Kelling et al., 1977). Values for other forage crops and corn in this and other studies ranged from not detected to 0.222 μg/g $(kg/ha)^{-1}$. Higher uptake slopes from pot studies were considered less appropriate. The highest uptake slope obtained in a field study for a crop consumed by humans was a value of 0.80 μg/g $(kg/ha)^{-1}$ for cabbage grown at a pH of 6.2 to 6.4 (Boyd et al., 1982). Values for other leafy vegetables ranged from 0.027 to 0.75 in acid soils, and from not detected to 0.068 in neutral soils. Slopes for most other crops were lower, many showing no detectable uptake of Ni. (See Section 4, pp. 4-12 to 4-16.)

v. **Background concentration in plant tissue (BP)**

Animal diet:
Rye forage   0.9 μg/g DW

Human diet:
Cabbage   1.7 μg/g DW

The values for the background concentrations in plant tissues were obtained from the same studies as used for the uptake slopes (i.e., Kelling et al., 1977; Boyd et al., 1982). They were the highest or among the highest background levels of Ni for animal and human consumed plants. (See Section 4, pp. 4-12 to 4-16.)

d. **Index 5 Values**

| Diet | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|---|
| Animal | Typical | 1.0 | 1.0 | 1.0 | 1.3 |
| | Worst | 1.0 | 1.1 | 1.9 | 8.4 |
| Human | Typical | 1.0 | 1.1 | 1.6 | 5.9 |
| | Worst | 1.0 | 2.5 | 16 | 120[a] |

[a]Value exceeds comparable value of Index 6; therefore may be precluded by phytotoxicity.

e. **Value Interpretation** - Value equals factor by which plant tissue concentration is expected to increase above background when grown in sludge-amended soil.

f. **Preliminary Conclusion** - Concentrations of Ni in plant tissues may increase above background concentrations except possibly for plants serving as animal feed when typical sludge is applied at low rates (5 and 50 mt/ha).

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

a. **Explanation** - Compares maximum plant tissue concentration associated with phytotoxicity with background concentration in same plant tissue. The purpose is to determine whether the plant concentration increments calculated in Index 5 for high applications are truly realistic, or whether such increases would be precluded by phytotoxicity.

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 phytotoxicity (PP)**

Animal diet:
Rye grass 160 μg/g DW

Human diet:
Swiss chard 170 μg/g DW

In a pot study, a tissue concentration of 160 μg/g in rye grass tops was the approximate threshold concentration for adverse effects in yield (Bolton et al., 1975). The concentration shown for Swiss chard (170 μg/g) was associated with yield reductions of 37 percent (Valdares et al., 1983). (See Section 4, pp. 4-8 to 4-11).

ii. **Background concentration in plant tissue (BP)**

Animal diet:
Rye grass 10 μg/g DW

Human diet:
Swiss chard 10 μg/g DW

Values for the background concentrations of Ni in plant tissues were selected from the same studies used for the phytotoxicity data (Bolton et al., 1975; Valdares et al., 1983). They are however, the highest or among the highest values available for such crops. (See Section 4, pp. 4-8 to 4-11.)

d. **Index 6 Values**

| Plant | Index Value |
|---|---|
| Rye grass | 16 |
| Swiss chard | 17 |

e. **Value Interpretation** - Value gives the maximum factor of tissue concentration increment (above background) which is permitted by phytotoxicity. Value is compared with values for the same or similar plant tissues given by Index 5. The lowest of the two indices indicates the maximal increase which can occur at any given application rate.

f. **Preliminary Conclusion** - The increased plant tissue concentrations of Ni expected to result from landspreading of sludge may be precluded by phytotoxicity for plants in the human diet when sludge containing a high concentration of Ni is applied at a high rate (500 mt/ha).

## 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 food 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.9 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-7).

iii. **Feed concentration toxic to herbivorous animal (TA) = 100 μg/g DW**

Decreased food intake in calves was observed when Ni was added to the diet at 100 μg/g DW as $NiCl_2$ (O'Dell et al., 1970). (See Section 4, p. 4-17.)

d. **Index 7 Values**

| Sludge Concentration | Sludge Application Rate (mt/ha) | | | |
|---|---|---|---|---|
| | 0 | 5 | 50 | 500 |
| Typical | 0.0090 | 0.0090 | 0.0093 | 0.012 |
| Worst | 0.0090 | 0.0098 | 0.017 | 0.076 |

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** - Landspreading of sludge is not expected to result in plant tissue concentrations of Ni that pose a toxic hazard 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 | 44.7 μg/g DW |
| Worst | 662.7 μg/g DW |

See Section 3, p. 3-1.

ii. **Background concentration of pollutant in soil (BS)** = 18.6 μg/g DW

See Section 3, p. 3-2.

iii. **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.

iv. **Feed concentration toxic to herbivorous animal (TA) = 100 μg/g DW**

See Section 3, p. 3-9.

d. **Index 8 Values**

| Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|
| Typical | 0.0093 | 0.022 | 0.022 | 0.022 |
| Worst | 0.0093 | 0.33 | 0.33 | 0.33 |

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 result in a toxic hazard due to Ni for grazing animals that inadvertently ingest sludge-amended soil.

E. **Effect on Humans**

1. **Index of Human Toxicity 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 acceptable daily intake (ADI) 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 as the most responsive plant(s) (as chosen in Index 5). 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for a human diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) =** 1.7 μg/g DW

The background concentration value used is for the plant chosen for the human diet (see Section 3, p. 3-7).

iii. **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 (1984). 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 estimated dry-weight consumption of all non-fruit crops.

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

| | |
|---|---|
| Toddler | 135 µg/day |
| Adult | 400 µg/day |

Estimates of average total daily intake of Ni range from 165 to 600 µg/day. An average value of 400 µg/day for adults was selected by an expert panel for use in risk assessment (U.S. EPA, 1985). The present analysis indicates that total Ni intake for toddlers would be about one-third of the adult amount of approximately 135 µg/day. (See Section 4, p. 4-3.)

v. **Acceptable daily intake of pollutant (ADI) =** 3500 µg/day

Based on a chronic no-observed-adverse-effect-level (NOAEL) of 100 ppm in the diet of rats (Ambrose et al., 1976), assuming the rat consumes 5 percent of its body weight daily, applying an uncertainty factor of 100, and assuming a human body weight of 70 kg (U.S. EPA, 1985), ADI is calculated to be 3500 µg/day for Ni in food. Ni in drinking water may be more readily absorbed, thus an ADI for aqueous Ni would be somewhat lower (U.S. EPA, 1985). Although calculated on a body weight basis of 70 kg, the value of 3500 µg/day is also considered to apply to infants and toddlers, because the uncertainty factor is considered sufficient to protect sensitive individuals. (See Section 4, p. 4-4.)

d. **Index 9 Values**

| Group | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|---|
| Toddler | Typical | 0.039 | 0.041 | 0.060 | 0.22 |
| | Worst | 0.039 | 0.093 | 0.57 | 4.4[a] |
| Adult | Typical | 0.11 | 0.12 | 0.17 | 0.60 |
| | Worst | 0.11 | 0.26 | 1.6 | 12[a] |

[a]Value may be precluded by phytotoxicity; see Indices 5 and 6.

e. **Value Interpretation** - Value equals factor by which expected intake exceeds ADI. Value > 1 indicates a possible human health threat. 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** - The consumption of plants grown on sludge-amended soil by humans is not expected to pose a toxic threat except possibly for adults when high-Ni sludge is applied at high rates (50 and 500 mt/ha) and for toddlers when high-Ni sludge is applied at a high rate (500 mt/ha). The concentrations of Ni in plants which are toxic to humans may be precluded by phytotoxicity when high-Ni sludge is applied at a high rate (500 mt/ha) (see Indices 5 and 6).

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

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

b. **Assumptions/Limitations** - Assumes that all animal products are from animals receiving all their feed from sludge-amended soil. The uptake slope of pollutant in animal tissue (UA) used is assumed to be representative of all animal tissue comprised by the daily human dietary intake (DA) used. 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. **Index of plant concentration increment caused by uptake (Index 5)**

Index 5 values used are those for an animal diet (see Section 3, p. 3-7).

ii. **Background concentration in plant tissue (BP) = 0.9 μg/g DW**

The background concentration value used is for the plant chosen for the animal diet (see Section 3, p. 3-7).

iii. **Uptake slope of pollutant in animal tissue (UA)** = 0.024 μg/g tissue DW (μg/g feed DW)$^{-1}$

Of animal products consumed by humans, beef liver was the most responsive in terms of Ni uptake, except kidney, which was regarded as comprising too small a portion of the U.S. diet. Uptake by muscle tissue was not significant in seven studies. The slope value is derived from a study in which cattle were given sludge-amended feed (Boyer et al., 1981). (See Section 4, p. 4-20.)

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

| | |
|---|---|
| Toddler | 0.97 g/day |
| Adult | 5.76 g/day |

The FDA Revised Total Diet (Pennington, 1983) lists average daily inake of beef liver (fresh weight) for various age-sex classes. The 95th percentile of liver consumption (chosen in order to be conservative) is assumed to be approximately 3 times the mean values. Conversion to dry weight is based on data from the U.S. Department of Agriculture (1975).

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

| | |
|---|---|
| Toddler | 135 μg/day |
| Adult | 400 μg/day |

See Section 3, p. 3-13.

vi. **Acceptable daily intake of pollutant (ADI)** = 3500 μg/day

See Section 3, p. 3-13.

d. **Index 10 Values**

| Group | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|---|
| Toddler | Typical | 0.039 | 0.039 | 0.039 | 0.039 |
| | Worst | 0.039 | 0.039 | 0.039 | 0.039 |
| Adult | Typical | 0.11 | 0.11 | 0.11 | 0.11 |
| | Worst | 0.11 | 0.11 | 0.11 | 0.11 |

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

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to pose a health hazard due to Ni for humans who consume animal products derived from animals that feed on plants grown in sludge-amended soil.

3. **Index of Human Toxicity 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 ADI.

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 three years old.

c. **Data Used and Rationale**

i. **Animal tissue** = Beef liver

Beef liver is an animal product that is considered to be normally found in the human diet.

ii. **Background concentration of pollutant in soil (BS)** = 18.6 µg/g DW

See Section 3, p. 3-2.

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

Typical 44.7 µg/g DW
Worst 662.7 µg/g DW

See Section 3, p. 3-1.

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

See Section 3, p. 3-10.

v. **Uptake slope of pollutant in animal tissue (UA)** = 0.024 μg/g tissue DW (μg/g feed DW)$^{-1}$

See Section 3, p. 3-15.

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

Toddler 0.97 g/day
Adult 5.76 g/day

See Section 3, p. 3-15.

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

Toddler 135 μg/day
Adult 400 μg/day

See Section 3, p. 3-13.

viii. **Acceptable daily intake of pollutant (ADI)** = 3500 μg/day

See Section 3, p. 3-13.

d. **Index 11 Values**

| Group | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|---|
| Toddler | Typical | 0.039 | 0.039 | 0.039 | 0.039 |
| | Worst | 0.039 | 0.039 | 0.039 | 0.039 |
| Adult | Typical | 0.11 | 0.11 | 0.11 | 0.11 |
| | Worst | 0.11 | 0.12 | 0.12 | 0.12 |

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

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to pose a health threat due to Ni for humans who consume animal products derived from animals that inadvertently ingest sludge-amended soil.

4. **Index of Human Toxicity 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 ADI.

**b. Assumptions/Limitations** - Assumes that the pica child consumes an average of 5 g/day of sludge-amended soil. If an ADI specific for a child is not available, this index assumes that the ADI 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 ADI provide protection for the child, taking into account the smaller body size and any other differences in sensitivity.

**c. Data Used and Rationale**

**i. Index of soil concentration increment (Index 1)**

See Section 3, p. 3-2.

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

Typical 44.7 μg/g DW
Worst 662.7 μg/g DW

See Section 3, p. 3-1.

**iii. Background concentration of pollutant in soil (BS) = 18.6 μg/g DW**

See Section 3, p. 3-2.

**iv. 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 (1984).

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

Toddler 135 μg/day
Adult 400 μg/day

See Section 3, p. 3-13.

**vi. Acceptable daily intake of pollutant (ADI) = 3500 μg/day**

See Section 3, p. 3-13.

d. **Index 12 Values**

| Group | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 | Pure Sludge |
|---|---|---|---|---|---|---|
| Toddler | Typical | 0.065 | 0.065 | 0.066 | 0.073 | 0.10 |
| | Worst | 0.065 | 0.067 | 0.088 | 0.25 | 0.99 |
| Adult | Typical | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| | Worst | 0.11 | 0.11 | 0.11 | 0.12 | 0.12 |

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

f. **Preliminary Conclusion** - Landspreading of sludge is not expected to pose a health threat due to Ni for humans who ingest sludge or sludge-amended soil.

5. **Index of Aggregate Human Toxicity (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 ADI.

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**

| Group | Sludge Concentration | Sludge Application Rate (mt/ha) 0 | 5 | 50 | 500 |
|---|---|---|---|---|---|
| Toddler | Typical | 0.065 | 0.067 | 0.088 | 0.25 |
| | Worst | 0.065 | 0.12 | 0.62 | 4.6[a] |
| Adult | Typical | 0.11 | 0.12 | 0.17 | 0.60 |
| | Worst | 0.11 | 0.27 | 1.6 | 12[a] |

[a]Value may be partially precluded by phytotoxicity; see Indices 9 and 10.

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

f. **Preliminary Conclusion** - The aggregate amount of Ni in the human diet resulting from landspreading of sludge is not expected to pose a health hazard except possibly for toddlers when high-Ni sludge is applied at a high rate (500 mt/na) and for adults when high-Ni sludge is applied at high rates (50 and 500 mt/ha). The concentration of Ni in plants which is toxic to humans may be partially precluded by phytotoxicity for high-Ni sludges applied at a high rate (500 mt/ha) (see Indices 5 and 6).

## II. LANDFILLING

### A. Index of Groundwater Concentration Increment 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 Exposure Assessment Group (EAG) model, "Rapid Assessment of Potential Groundwater Contamination Under Emergency Response Conditions" (U.S. EPA, 1983c). 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; 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.

ii. **Site parameters**

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

Sikora et al. (1982) monitored several landfills 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 of 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 | 44.7 mg/kg DW |
| Worst | 662.7 mg/kg DW |

See Section 3, p. 3-1.

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

The degradation rate in the unsaturated zone is assumed to be zero for all inorganic chemicals.

(c) **Soil sorption coefficient ($K_d$)**

| | |
|---|---|
| Typical | 58.6 mL/g |
| Worst | 12.2 mL/g |

$K_d$ values were obtained from Gerritse et al. (1982) using sandy loam soil (typical) or sandy soil (worst). Values shown are geometric means of a range of values derived using sewage sludge solution phases as the liquid phase in the adsorption experiments.

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 (1983c).

**(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 (1983c).

**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 pre-existing 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 pre-existing 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) = 4.8 μg/L**

The only available information on ambient background levels of Ni in water is for surface waters. In a study of 969 U.S. public water supplies for 1969 to 1970 (U.S. EPA, 1980), Ni concentrations varied from <0.001 mg/L to 0.075 mg/L. The average value of 4.8 μg/L is used in lieu of a value for groundwater. (See Section 4, p. 4-2.)

(c) **Soil sorption coefficient ($K_d$) = 0 mL/g**

Adsorption is assumed to be zero in the saturated zone.

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

5. **Value Interpretation** - Value equals factor by which expected groundwater concentration of pollutant at well exceeds the background concentration (a value of 2.0 indicates the concentration is doubled, a value of 1.0 indicates no change).

6. **Preliminary Conclusion** - Landfilling of sludge may increase Ni concentrations in groundwater at the well above background concentrations; this increase may be large when all worst-case conditions prevail at a disposal site.

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

1. **Explanation** - Calculates human exposure which could result from groundwater contamination. Compares exposure with acceptable daily intake (ADI) 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 increment resulting from landfilled sludge (Index 1)**

See Section 3, p. 3-27.

b. **Background concentration of pollutant in groundwater (BC) = 4.8 μg/L**

See Section 3, p. 3-25.

c. **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.

d. **Average daily human dietary intake of pollutant (DI) = 400 μg/day**

See Section 3, p. 3-13.

TABLE 3-1. INDEX OF GROUNDWATER CONCENTRATION INCREMENT RESULTING FROM LANDFILLED SLUDGE (INDEX 1) AND INDEX OF HUMAN TOXICITY 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 | 1.3 | 4.8 | 1.3 | 1.3 | 2.3 | 11 | 800 | 0 |
| Index 2 Value | 0.11 | 0.12 | 0.11 | 0.11 | 0.12 | 0.14 | 2.3 | 0.11 |

[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 ($P_{dry}$) and volumetric water content ($\theta$).

[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 ($\alpha$).

e. **Acceptable daily intake of pollutant (ADI)** = 3500 μg/day

See Section 3, p. 3-13.

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

5. **Value Interpretation** - Value equals factor by which pollutant intake exceeds ADI. Value >1 indicates a possible human health threat. Comparison with the null index value indicates the degree to which any hazard is due to landfill disposal, as opposed to preexisting dietary sources.

6. **Preliminary Conclusion** - Landfilling of sludge is not expected to pose a human health threat due to Ni from groundwater contamination except possibly when all worst-case conditions prevail at a disposal site.

## 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, 1979b). 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)** = $2.78 \times 10^{-7}$ 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 | 44.7 mg/kg DW |
| Worst | 662.7 mg/kg DW |

See Section 3, p. 3-1.

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

| | |
|---|---|
| Typical | 0.002 (unitless) |
| Worst | 0.006 (unitless) |

Emission estimates may vary considerably between sources; therefore, the values used are based on a U.S. EPA 10-city incineration study (Farrell and Wall, 1981). Where data were not available from the EPA study, a more recent report which thoroughly researched heavy metal emissions was utilized (CDM, 1983).

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) = 0.009 μg/m$^3$**

The value is the lowest estimate of Ni levels in ambient urban air nationally for the 1970-80 period (U.S. EPA, 1979a). (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 | 1.4 |
| | Worst | 1.0 | 1.4 | 7.6 |
| Worst | Typical | 1.0 | 1.1 | 2.3 |
| | Worst | 1.0 | 2.1 | 21 |

[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** - Incineration of sludge may increase air concentrations of Ni above background concentrations.

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. 3-30.

   b. **Background concentration of pollutant in urban air (BA)** = 0.009 $\mu g/m^3$

      See Section 3, p. 3-30.

   c. **Cancer potency** = 1.15 $(mg/kg/day)^{-1}$

      The cancer ptoency has been statistically derived by the U.S. EPA based on clinical and epidemiological studies linking the inhalation of Ni to nasal and lung cancers in industrial workers (U.S. EPA, 1983b). It is a point estimate which is based on a linear (non-threshold) model. (See Section 4, p. 4-5.)

   d. **Exposure criterion (EC)** = $3.04 \times 10^{-3}$ $\mu g/m^3$

      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 | 3.0 | 3.0 | 4.3 |
| | Worst | 3.0 | 4.1 | 22 |
| Worst | Typical | 3.0 | 3.2 | 6.9 |
| | Worst | 3.0 | 6.2 | 61 |

[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 may slightly increase the human cancer risk due to inhalation of Ni above the risk posed by background urban air concentrations of Ni. An increase may not occur when sludge containing a typical concentration of Ni is incinerated at a low feed rate (2660 kg/hr DW), and a typical fraction of Ni is emitted through the stack.

## 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.

## SECTION 4

## PRELIMINARY DATA PROFILE FOR NICKEL IN MUNICIPAL SEWAGE SLUDGE

# I. OCCURRENCE

## A. Sludge

### 1. Frequency of Detection

83 to 93% — U.S EPA, 1982a (p. 41, 49)

### 2. Concentration

| | | |
|---|---|---|
| Minimum | 3 µg/g DW | Booz Allen and Hamilton, Inc., 1983 |
| Median | 53 µg/g DW | |
| Mean | 229.7 µg/g DW | |
| 90th percentile | 414 µg/g DW | |
| 95th percentile | 918 µg/g DW | |
| Maximum | 9450 µg/g DW | |
| Median | 44.7 µg/g DW | Statiscally derived from from sludge concentration data presented in U.S. EPA, 1982a |
| Geometric mean | 60.5 µg/g DW | |
| Mean | 136.5 µg/g DW | |
| 95th percentile | 662.7 µg/g DW | |

## B. Soil - Unpolluted

### 1. Frequency of Detection

Virtually 100%

### 2. Concentration

Unspecified soils (total Ni) — Allaway, 1968 (p. 242)
- "Normal" mean 40 µg/g DW
- Range 10 to 1000 µg/g DW

Ohio farm soils (total Ni) — Logan and Miller, 1983 (p. 14)
- Mean 18 µg/g DW
- Range 9 to 38 µg/g DW

U.S. cropland soils (total Ni) — Holmgren, 1983
- Mean (±SD) 24.2 (±28.2) µg/g DW
- Median 18.6 µg/g DW
- Range >0.6 to 269 µg/g DW

Baltimore, MD garden soils (1N $HNO_3$ extractable) — Mielke et al., 1983

| | | |
|---|---|---|
| Mean (±SD) | 4.9 (±7.9) μg/g DW | |
| Median | 2.8 μg/g DW | |
| Range | 0.5 to 53.4 μg/g DW | |

Minnesota surface soils (total Ni) — Pierce et al., 1982 (p. 418)

| | | |
|---|---|---|
| Mean (±SD) | 18 (±10) μg/g DW | |
| Range | 7 to 66 μg/g DW | |

C. **Water - Unpolluted**

1. **Frequency of Detection**

Data not immediately available.

2. **Concentration**

a. **Freshwater**

| | | |
|---|---|---|
| North American Rivers | | Hem, 1970 |
| Median | 10 μg/L | (p. 201) |
| Natural freshwaters | | U.S. EPA, 1980 |
| Normal | >1 μg/L | (p. B-1) |

b. **Seawater**

Data not immediately available.

c. **Drinking Water**

| | | |
|---|---|---|
| Median | <2.7 μg/L | Hem, 1970 |
| Mean | 4.8 μg/L | (p. 201) |
| 99th percentile | 20 μg/L | U.S. EPA, 1980 (p. C-4) |
| Maximum | 75 μg/L | U.S. EPA, 1980 (p. C-3) |

D. **Air**

1. **Frequency of Detection**

| | | |
|---|---|---|
| Urban | 30 to 70% | U.S. EPA, 1979a (p. 22) |
| Rural | 5 to 30% | U.S. EPA, 1979a (p. 25) |

2. **Concentration**

| | |
|---|---|
| Urban U.S. 1970-1980 | U.S. EPA, 1979a (p. 22) |
| Median 0.009 to 0.017 μg/m$^3$ | |
| Mean 0.009 to 0.024 μg/m$^3$ | |
| Range 0.009 to 0.639 μg/m$^3$ | |
| Rural U.S. 1970-1976 | U.S. EPA, 1979a (p. 25) |
| Median <0.009 μg/m$^3$ | |
| Mean <0.009 μg/m$^3$ | |
| Range <0.009 to 0.280 μg/m$^3$ | |

E. **Food**

1. **Total Average Intake**

| | |
|---|---|
| American adults 300 to 600 μg/day | U.S. EPA, 1980 (p. C-7) |
| 500 μg/day | U.S. EPA, 1980 (p. C-7) |
| 400 μg/day | U.S. EPA, 1985 |
| Institutionalized children, 9 to 12 years old from 28 U.S. cities = 451 μg/day | U.S. EPA, 1980 (p. C-7) |
| Nine institutional diets, U.S. = 165 μg/day | U.S. EPA, 1980 (p. C-7) |
| Daily fecal Ni excretion, adults = 258 μg/day | U.S. EPA, 1980 (p. C-7) |

2. **Concentration**

Data not immediately available.

II. **HUMAN EFFECTS**

A. **Ingestion**

1. **Carcinogenicity**

a. **Qualitative Assessment**

| | |
|---|---|
| No evidence of carcinogenicity induced by ingested Ni. | U.S. EPA, 1980 (p. C-131)<br>U.S. EPA, 1983b (p. 46) |

b. **Potency**

None demonstrated for ingestion route.

c. **Effects**

None demonstrated for ingestion route.

2. **Chronic Toxicity**

a. **ADI**

| | |
|---|---|
| ADI of 31 μg/day published by U.S. EPA is not valid because of methodological deficiencies in the study on which it was based. | U.S. EPA, 1980 (p. C-133) |
| ADI of 3.5 mg/day based on chronic NOAEL of 100 ppm in diet of rats. | U.S. EPA, 1985 |

b. **Effects**

| | |
|---|---|
| In rats given 5 mg/L in drinking water, reduced litter size, increased number of runts and neo-natal mortality were observed. | Schroeder and Mitchener, 1971 |
| In rats given 1000 mg/kg of diet, body weight reduction was observed. | Ambrose et al., 1976 |

3. **Absorption Factor**

| | |
|---|---|
| 1 to 10% | U.S. EPA, 1980 (p. C-21) |

4. **Existing Regulations**

| | |
|---|---|
| Ambient Water Quality Criteria (Revised, 1982) = 632 μg/L | U.S. EPA, 1982b |

B. **Inhalation**

1. **Carcinogenicity**

a. **Qualitative Assessment**

| | |
|---|---|
| IARC rating: Group 1, "carcinogenic to humans" for the Ni refining process; Group 2A, "probably carcinogenic to humans" for Ni and certain Ni compounds (especially Ni subsulfide and Ni oxide) | International Agency for Research on Cancer (IARC), 1982 (p. 167) |

b. **Potency**

| | |
|---|---|
| Unit risk (at 1 μg $Ni/m^3$) = $3.3 \times 10^{-4}$<br>Cancer potency = 1.15 $(mg/kg/day)^{-1}$ | U.S. EPA, 1983b (p. 136) |

c. **Effects**

| | |
|---|---|
| Lung, laryngeal, and nasal tumors | U.S. EPA, 1983b (p. 137) |

2. **Chronic Toxicity**

a. **Inhalation Threshold or MPIH**

See below, "Existing Regulations"

b. **Effects**

| | |
|---|---|
| Asthma, pulmonary fibrosis, and pulmonary edema are putative effects of Ni in welders using Ni alloys. Pneumoconiosis, pneumonia, alveolar hyperplasia, and mild irritation of the lung have been observed in Ni-exposed animals | American Conference of Governmental and Industrial Hygienists (ACGIH), 1980 (p. 294-300) |

3. **Absorption Factor**

| | |
|---|---|
| Negligible for Ni contained in welding fumes, probably Ni oxides. Considerable for Ni carbonyl (∿50%) and Ni chloride (∿75%). | U.S. EPA, 1983b (p.33) |

4. **Existing Regulations**

ACGIH Threshold Limit Values ($\mu g/m^3$) — ACGIH, 1981 (p. 23)

| | TLV TWA | TLV STEL |
|---|---|---|
| Ni metal | 1 | |
| Soluble Ni compounds | 0.1 | 0.3 |
| Ni sulfide roasting, fume and dust (as Ni) | 1 | |

| | |
|---|---|
| OSHA Standard<br>Ni carbonyl 7 $\mu g/m^3$ (8-hr TWA)<br>Ni, inorganic and compounds 1 $mg/m^3$ (8-hr TWA) | Centers for Disease Control (CDC), 1983 (p. 17S) |
| NIOSH Recommended Exposure Limit<br>Ni carbonyl 7 $\mu g/m^3$ (10-hr TWA)<br>Ni, inorganic and compounds 15 $\mu g/m^3$ (10-hr TWA) | CDC, 1983 (p. 17S) |

## III. PLANT EFFECTS

### A. Phytotoxicity

See Table 4-1.

### B. Uptake

See Table 4-2.

## IV. DOMESTIC ANIMAL AND WILDLIFE EFFECTS

### A. Toxicity

See Table 4-3.

### B. Uptake

See Table 4-4.

## V. AQUATIC LIFE EFFECTS

### A. Toxicity

#### 1. Freshwater

**a. Acute**

| Hardness (mg/L as $CaCO_3$) | Criterion (μg/L) | U.S. EPA, 1980 (p. B-11) |
|---|---|---|
| 50 | 1100 | |
| 100 | 1800 | |
| 200 | 3100 | |

**b. Chronic**

| Hardness (mg/L as $CaCO_3$) | Criterion (μg/L) | U.S. EPA, 1980 (p. B-11) |
|---|---|---|
| 50 | 56 | |
| 100 | 96 | |
| 200 | 160 | |

#### 2. Saltwater

**a. Acute**

140 μg/L

**b. Chronic**

7.1 μg/L

**B. Uptake**

| | |
|---|---|
| Fish, whole<br>Range NA<br>Mean 61 | U.S. EPA, 1980 (p. B-25) |
| Bivalve mollusks, soft parts<br>Range 299 to 416<br>Mean 354 | U.S. EPA, 1980 (p. B-25) |

## VI. SOIL BIOTA EFFECTS

**A. Toxicity**

See Table 4-5.

**B. Uptake**

See Table 4-6.

## VIII. PHYSIOCOCHEMICAL DATA FOR ESTIMATING FATE AND TRANSPORT

Atomic weight: 5870
Melting point: 1555°C
Boiling point: 2837°C
Density: 8.90
Heat capacity (25°C): 6.23 cal/g-atom/°C
Moh's hardness: 3.8
Latent heat of fusion: 73 cal/g

Merck Index, 1976 (pp. 6312 to 6313)

## TABLE 4-1. PHYTOTOXICITY OF NICKEL

| Plant/Tissue | Chemical Form Applied | Soil pH | Control Tissue Concentration (μg/g DW) | Experimental Soil Concentration (μg/g DW) | Experimental Application Rate (kg/ha) | Experimental Tissue Concentration (μg/g DW) | Effect | References |
|---|---|---|---|---|---|---|---|---|
| Ryegrass/tops | sludge (pot) | 5.0-6.5 | 10-20 | NR[a] | NA[b] | 160 | Threshold concentration for adverse effects on yield | Bolton, 1975 |
| Corn/tops | high-Ni sludge (pot) | 6.5 | <4.5 | 190 | NA | NR | No yield reduction | Cunningham et al., 1975a |
| | | | | 380 | | | Yield reduced 32-84% compared to control | |
| Rye/tops | high-Ni sludge (pot) | 6.5 | <4.5 | 190 | NA | NR | No yield reduction | Cunningham et al., 1975a |
| | | | | 380 | | | Yield not reduced compared to controls, but reduced 34% compared to lower sludge application. | |
| Agronomic crop tissues | NA | NA | NA | NA | NA | 3 | Suggested tolerance level | Cunningham et al., 1975a |
| Lettuce/shoots | Ni-enriched sludge (pot) | 5.7 | 3.5 | 40 | NA | 41 | Yield reduced 13% | Mitchell et al., 1978 |
| | | | | 80 | | 241 | Yield reduced 30% | |
| | | | | 160 | | 345 | Yield reduced 75% | |
| | | 7.5 | 4.5 | 160 | NA | 29 | Yield not significantly reduced | |
| | | | | 320 | | 61 | Yield reduced 35% | |
| | | | | 640 | | 166 | Yield reduced 95% | |

TABLE 4-1. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Control Tissue Concentration (µg/g DW) | Experimental Soil Concentration (µg/g DW) | Experimental Application Rate (kg/ha) | Experimental Tissue Concentration (µg/g DW) | Effect | References |
|---|---|---|---|---|---|---|---|---|
| Swiss chard | sludge (pot) | 6.9-7.6 | 5 | 200 | NA | 39 | Yield not reduced | Valdares et al., 1983 |
| | | 5.4-7.2 | <10 | 46 | | 85 | Yield not reduced | |
| | | 5.4-6.8 | <10 | 50 | | 160 | Yield reduced 28%[c] | |
| | | 5.3-7.1 | <10 | 73 | | 180 | Yield reduced 74%[c] | |
| | | 4.8-6.1 | <10 | 66 | | 70 | Yield not reduced | |
| | | 4.7-6.0 | <10 | 73 | | 170 | Yield reduced 37%[c] | |
| | | 4.6-6.0 | <10 | 100 | | 250 | Yield reduced 82%[c] | |
| Red beet/ total | high-Ni | 6.1-7.0 | NR | NR | 94[d] | NR | Yield reduced 25% | Webber, 1972 |
| | sludge (field) | | | | 251[e] | | Yield reduced 48% | |
| Celery/ marketable | high-Ni sludge (field) | 6.1-7.0 | NR | NR | 94[d] | NR | Yield not significantly reduced | Webber, 1972 |
| | | | | | 251[e] | | Yield reduced 23% | |
| | | | | | 502[e] | | Yield reduced 70% | |
| Oats/shoot | Ni-enriched sludge (pot) | 5.5 | NR | 12.5 | NA | NR | No height reduction | Webber, 1972 |
| | | | | 25 | | | Height reduced 27% | |
| | | | | 37.5 | | | Height reduced 53% | |

TABLE 4-1. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Control Tissue Concentration (µg/g DW) | Experimental Soil Concentration (µg/g DW) | Experimental Application Rate (kg/ha) | Experimental Tissue Concentration (µg/g DW) | Effect | References |
|---|---|---|---|---|---|---|---|---|
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 5.7 | 2.3<br><1.0 | 40<br>40 | NA | 16<br>22 | Grain yield not significantly reduced | Mitchell et al., 1978 |
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 5.7 | 2.3<br><1.0 | 80<br>80 | NA | 46<br>64 | Grain yield reduced 22% | |
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 5.7 | 2.3<br><1.0 | 160<br>160 | NA | 125<br>119 | Grain yield reduced 40% | |
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 7.5 | 3.4<br><1.0 | 160<br>160 | NA | 6.8<br>5.1 | Grain yield not significantly reduced | |
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 7.5 | 3.4<br><1.0 | 320<br>320 | NA | 18<br>26 | Grain yield reduced 37% | |
| Wheat/leaves<br>Wheat/grain | Ni-enriched sludge (pot) | 7.5 | 3.4<br><1.0 | 640<br>640 | NA | 41<br>50 | Grain yield reduced 80% | Mitchell et al., 1978 |

TABLE 4-1. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Control Tissue Concentration (μg/g DW) | Experimental Soil Concentration (μg/g DW) | Experimental Application Rate (kg/ha) | Experimental Tissue Concentration (μg/g DW) | Effect | References |
|---|---|---|---|---|---|---|---|---|
| Oats | $NiSO_4$ (pot) | 6.4 | NR | 50 | NA | NR | Yield reduced 15% | Webber, 1972 |
| | | | | 100 | | | Yield reduced 26% | |
| | | | | 250 | | | Yield reduced 30% | |
| | | 5.7 | NR | 50 | NA | NR | Yield reduced 16% | |
| | | | | 100 | | | Yield reduced 71% | |
| | | | | 250 | | | Yield reduced 88% | |
| Mustard | $NiSO_4$ (pot) | 6.4 | NR | 100 | NA | NR | No yield reduction | Webber, 1972 |
| | | | | 250 | | | Yield reduced 69% | |
| | | 5.7 | NR | 50 | NA | NR | Yield reduced 31% | |
| | | | | 100 | | | Yield reduced 97% | |
| Corn/grain | sludge (field) | 7.3 | 0.5-1.6 | NR | <180[f] | <4.0 | No yield reduction | Hinesly et al., 1984 |
| Corn/leaf | sludge (field) | sandy soil | 0.3 | NR | 165 | 3.0 | No grain yield reduction | CAST, 1976 (p. 46) |
| Corn/grain | | sandy soil | 0.3 | NR | 165 | 4.0 | | |

[a]NR = Not reported.
[b]NA = Not applicable.
[c]Since sludge was applied, effect may not be due to Ni alone.
[d]Cumulative application during 3 years.
[e]Single application 3 years prior to cropping.
[f]Cumulative application during 10 years.

TABLE 4-2. UPTAKE OF NICKEL BY PLANTS

| Plant/Tissue | Chemical Form Applied | Soil pH | Range (N) of Application Rates (kg/ha)[a] | Control Tissue Concentration (µg/g DW) | Uptake Slope[b] | References |
|---|---|---|---|---|---|---|
| Ryegrass/tops | sludge (pot) | 6.5 | 0-120[c] (4) | 10 | 0.55 | Bolton, 1975 |
| | | 5.0 | 0-120[c] (4) | 20 | 0.67 | |
| Romaine lettuce | sludge (field) | 6.2-7.7 | 0-59 (6) | 1.8 | NS[i] | Chaney |
| | | 5.3-5.6 | 0-59 (3) | 1.6 | 0.044 | et al., 1982 |
| Swiss chard | sludge (field) | 6.7-7.7 | 0-59 (6) | 1.7 | 0.053 | Chaney |
| | | 5.7-6.3 | 0-59 (3) | 2.9 | 0.12 | et al., 1982 |
| Collard greens | sludge (field) | 6.3-7.7 | 0-59 (6) | 1.8 | 0.033 | Chaney |
| | | 5.5-6.3 | 0-59 (3) | 2.9 | 0.027 | et al., 1982 |
| Reed canary grass | sludge (field) | 6.2-7.4 | 0-1.45 (2)[d] | 2.4 | NS | Duncomb et al., 1982 |
| Corn/leaf | sludge (field) | 6.2-7.4 | 0-1.24 (2)[d] | 0.9 | NS | Duncomb et al., 1982 |
| Corn/grain | sludge (field) | 6.2-7.4 | 0-1.24 (2)[d] | 0.6 | NS | Duncomb et al., 1982 |
| Green pepper/edible | sludge (pot) | 7.1 | 0-33.8 (2)[c] | 0.4 | 0.033 | Furr et al., |
| | | 4.9 | 0-33.8 (2)[c] | 0.4 | 0.056 | 1981 |
| Kohlrabi/edible | sludge (pot) | 7.1 | 0-33.8 (2)[c] | 0.3 | 0.030 | Furr et al., |
| | | 4.9 | 0-33.8 (2)[c] | 0.9 | 0.13 | 1981 |

TABLE 4-2. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Range (N) of Application Rates (kg/ha)[a] | Control Tissue Concentration (μg/g DW) | Uptake Slope[b] | References |
|---|---|---|---|---|---|---|
| Lettuce/edible | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 0.8<br>0.6 | 0.027<br>0.071 | Furr et al., 1981 |
| Peas/edible | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 1.3<br>1.7 | 0.033<br>0.11 | Furr et al., 1981 |
| Spinach/edible | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 0.7<br>1.0 | 0.068<br>0.086 | Furr et al., 1981 |
| Sweet potato/edible | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 0.1<br>0.3 | 0.012<br>0.027 | Furr et al., 1981 |
| Turnip/edible | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 0.2<br>0.7 | 0.021<br>0.068 | Furr et al., 1981 |
| Apple/fruit | sludge (pot) | 7.1<br>4.9 | 0-33.8 (2)[c]<br>0-33.8 (2)[c] | 0.1<br>0.2 | 0.009<br>NS | Furr et al., 1981 |
| Corn/grain | sludge (field) | 7.3 | 0-180 (4)[e] | 0.5 | 0.009 | Hinesly et al., 1984 |
| Corn/leaf<br>Corn/grain | sludge (field) | sandy soil | 0-165 (4)[f]<br>0-165 (4)[f] | 0.3<br>0.3 | 0.017<br>0.022 | CAST, 1976 (p. 46) |
| Lettuce/leaf | sludge (field) | 6.4 | 0-4.48 (2) | 2.4 | NS | CAST, 1976 (p. 48) |

TABLE 4-2. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Range (N) of Application Rates (kg/ha)[a] | Control Tissue Concentration (µg/g DW) | Uptake Slope[b] | References |
|---|---|---|---|---|---|---|
| Broccoli/edible | sludge (field) | 6.4 | 0-4.48 (2) | 3.3 | NS | CAST, 1976 (p. 48) |
| Potato/edible | sludge (field) | 6.4 | 0-4.48 (2) | 0.8 | NS | CAST, 1976 (p. 48) |
| Tomato/edible | sludge (field) | 6.4 | 0-4.48 (2) | 1.3 | NS | CAST, 1976 (p. 48) |
| Cucumber/edible | sludge (field) | 6.4 | 0-4.48 (2) | 0.1 | 0.067 | CAST, 1976 (p. 48) |
| Eggplant/edible | sludge (field) | 6.4 | 0-4.48 (2) | 1.1 | NS | CAST, 1976 (p. 48) |
| String bean/edible | sludge (field) | 6.4 | 0-4.48 (2) | 7.6 | NS | CAST, 1976 (p. 48) |
| Rye/forage | sludge (field) | 5.0-6.0 | 0-42 (6) | 0.9 | 0.026 | Kelling et al., 1977 |
| Sorghum-sudan/ forage | sludge (field) | 5.0-6.0 | 0-42 (6) | 2.5 | 0.005 | Kelling et al.,1977 |
| Turnip/greens | sludge (field) | 5.6 | 0-8.5 (3)[g] | 3.0 | 0.75 | Miller and Boswell, 1979 |

TABLE 4-2. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Range (N) of Application Rates (kg/ha)[a] | Control Tissue Concentration (μg/g DW) | Uptake Slope[b] | References |
|---|---|---|---|---|---|---|
| Fodder rape/tops | sludge (pot) | 5.6 | 0-4.6 (3) | 1.34 | NS | Narwal et al., 1983 |
| | | 6.0 | 0-4.6 (3) | 0.24 | 0.030 | |
| | | 7.5 | 0-4.6 (3) | 0.11 | 0.076 | |
| Lettuce/shoots | Ni-enriched sludge (pot) | 5.7 | 0-1280 (9)[c] | 3.5 | 1.0 | Mitchell et al., 1978 |
| | | 7.5 | 0-1280 (9)[c] | 4.5 | 0.12 | |
| Wheat/leaves | Ni-enriched sludge (pot) | 5.7 | 0-640 (8)[c] | 2.3 | 0.46 | Mitchell et al., 1978 |
| Wheat/grain | | | 0-640 (8)[c] | <1.0 | 0.39 | |
| Wheat/leaves | Ni-enriched sludge (pot) | 7.5 | 0-1280 (9)[c] | 3.4 | 0.029 | Mitchell et al., 1978 |
| Wheat/grain | | | 0-1280 (9)[c] | <1.0 | 0.040 | |
| Corn/tops | Ni-enriched sludge (pot) | 6.8 | 0-162 (4)[c] | <4.5 | 0.087 | Cunningham et al., 1975b |
| Corn/tops | Ni-enriched sludge (pot) | 6.8 | 0-162 (4)[c] | <4.5 | 0.19 | Cunningham et al., 1975b |
| Cabbage | sludge ash (pot) | 5.2-5.7 | <420[c,h] | 0.6 | NS[h] | Furr et al., 1979 |
| Bean/edible | sludge (field) | 6.2-6.4 | 0-16.2 (2) | 6.1 | 0.019 | Boyd et al., 1982 |
| Beet/edible | sludge (field) | 6.2-6.4 | 0-16.2 (2) | 1.0 | 0.23 | Boyd et al., 1982 |

TABLE 4-2. (continued)

| Plant/Tissue | Chemical Form Applied | Soil pH | Range (N) of Application Rates (kg/ha)[a] | Control Tissue Concentration (μg/g DW) | Uptake Slope[b] | References |
|---|---|---|---|---|---|---|
| Cabbage/edible | sludge (field) | 6.2-6.4 | 0-16.2 (2) | 1.7 | 0.80 | Boyd et al., 1982 |
| Squash/edible | sludge (field) | 6.2-6.4 | 0-16.2 (2) | 1.9 | 0.28 | Boyd et al., 1982 |

a = Number of application rates, including control.
b = Slope y/x ; x = kg/ha applied; y = μg/g DW plant tissue concentration.
c = Application rate estimated from Ni additions to potted soil based on assumption of 1 μg Ni/g soil = 2 kg Ni/ha.
d = Cumulative application during 5 years. Applications to canary grass were made immediately after cutting and before regrowth.
e = Cumulative appliation during 10 years.
f = Cumulative appliation during 4 years.
g = Cumulative appliation during 2 years.
h = Sludge ashes from 10 different cities were used. No relationship between Ni content and uptake was found.

TABLE 4-3. TOXICITY OF NICKEL TO DOMESTIC ANIMALS AND WILDLIFE

| Species (N)[a] | Chemical Form Fed | Feed Concentration (μg/g DW) | Water Concentration (mg/L) | Daily Intake (mg/kg DW) | Duration | Effects | References[b] |
|---|---|---|---|---|---|---|---|
| Calves (6) | $NiCO_3$ | 250<br>500-1000 | NA[c] | NR[d] | 5 days | No adverse effect<br>Decreased food intake | O'Dell et al., 1970 |
| | $NiCl_2$ | 50<br>100-200 | NA | NR | 5 days | No adverse effect<br>Decreased food intake | |
| Cattle (6) | $NiCO_3$ | <250<br>1000 | NA | NR | 8 weeks | No adverse effect<br>Decreased food intake, growth rate, organ size and nitrogen retention | O'Dell et al., 1970 |
| Cattle, sheep, horse | NR | 50 | NA | NR | NR | Maximum tolerable level in feed | NAS, 1980 |
| Poultry | NR | 300 | NA | NR | NR | Maximum tolerable level in feed | NAS, 1980 |
| Chicken (24) | $NiSO_4$ | <300<br>500-1300 | NA | NR | 4 weeks | No adverse effect<br>Decreased growth and nitrogen retention | Weber and Reid, 1968 |
| | Ni acetate | <300<br>500-700<br>900-1300 | NA | NR | 4 weeks | No adverse effect<br>Decrease growth and nitrogen retention | |
| Swine | NR | 100 | NA | NR | NR | Maximum tolerable level in feed | NAS, 1980 |

TABLE 4-3. (continued)

| Species (N)[a] | Chemical Form Fed | Feed Concentration (μg/g DW) | Water Concentration (mg/L) | Daily Intake (mg/kg DW) | Duration | Effects | References[b] |
|---|---|---|---|---|---|---|---|
| Dog (6) | $NiSO_4$ | 100<br>1000<br>2500 | NA | NR | 2 years | No adverse effect<br>No adverse effect<br>Initially: emesis. After acclimation: decreased body weight and hemoglobin; increased urine volume, liver and kidney weights; granulocytic hyperplasia of bone marrow; lung pathologies. | Ambrose et al., 1976 |
| Rat (104) | soluble Ni salt | NA | 5 | NR | lifetime | No adverse effect | Schroeder et al., 1974 |
| Rat (10) | soluble Ni salt | NA | 5 | NR | 3 generations | Young: deaths and runts (F1-3 generations) | Schroeder and Mitchener, 1971 |
| Rat (6) | Ni acetate | 100<br>500<br>1000 | NA | NR | 6 weeks | No adverse effect<br>Decreased growth<br>Weight loss; decreased hemoglobin | Whanger, 1973 |
| Rat (50) | $NiSO_4$ | 100[e]<br>1000-2000[e] | NA | NR | 2 years | No adverse effect<br>Decreased body and liver weight; increased heart rate | Ambrose et al., 1976 |

TABLE 4-3. (continued)

| Species (N)[a] | Chemical Form Fed | Feed Concentration (µg/g DW) | Water Concentration (mg/L) | Daily Intake (mg/kg DW) | Duration | Effects | References[b] |
|---|---|---|---|---|---|---|---|
| Rat (60) | $NiSO_4$ | 250 | NA | NR | 3 generations | Increased stillborns in $F_1$ generation. | Ambrose et al., 1976 |
| | | 500 | | | | Increased stillborns in $F_1$ generation; fewer pups weaned in all generations | |
| Mouse (104) | nickelous acetate | NA | 5 | NR | lifetime | No adverse effect | Schroeder et al., 1963, 1964 |
| Mouse (12) | nickel acetate | 1100 | NA | NR | 4 weeks | Decreased growth in females | Weber and Reid, 1969 |
| | | 1600 | | | | Decreased growth | |
| Monkey (2) | Ni carbonate | 250-1000 | NA | NR | 6 months | No adverse effect | Phatak and Patwardhan, 1950 |
| | Ni soaps | 250-1000 | NA | NR | 6 months | No adverse effect | |

[a]N = Number of animals/treatment group.
[b]Source of all information in table is NAS, 1980 (p. 6, 345-363).
[c]NA = Not applicable.
[d]NR = Not reported.
[e]Administered in milk (µg/g WW).

TABLE 4-4. UPTAKE OF NICKEL BY DOMESTIC ANIMALS AND WILDLIFE

| Species (N)[a] | Chemical Form Fed | Range (N) of Feed Concentrations[b] (μg/g DW) | Tissue Analyzed | Control Tissue Concentration (μg/g DW)[c] | Uptake Slope[c,d] | References |
|---|---|---|---|---|---|---|
| Cattle (6) | sludge | 0.88-4.6 (2) | kidney | 0.14 | 0.005 | Boyer et al., 1981 |
| | | | liver | 0.14 | 0.024 | |
| | | | muscle | 0.31 | NS[f] | |
| Sheep (10) | sludge-grown corn silage | 1.40-2.26 (2) | kidney | 0.19 | 0.19 | Telford et al., 1982 |
| | | | liver | 0.06 | NS | |
| | | | muscle | 0.03 | NS | |
| Sheep (NR) | sludge-grown corn silage | NR[g] | muscle | NR | NS | Bray et al., 1981 |
| Swine (28) | sludge-grown corn grain | 1.60-3.30 (2) | kidney | 2.12 | 1.12 | Lisk et al., 1982 |
| | | | liver | 0.97 | NS | |
| | | | muscle | 0.94 | NS | |
| Swine (12)[e] | sludge | 2.75-123.8 (2) | kidney | 0.091 | 0.020 | Osuna et al., 1981 |
| | | | liver | ND | NS | |
| | | | muscle | ND | NS | |
| Rat (2) | sludge-grown cabbage | 0.42-3.68 | kidney | 0.2 | NS | Boyd et al., 1982 |
| | | | liver | 0.2 | NS | |
| | | | muscle | 0.2 | 0.12 | |

[a]N = Number of animals/treatment group.
[b]N = Number of feed concentrations, including control.
[c]When tissue values were reported as wet weight, unless otherwise indicated a moisture content of 77% was assumed for kidney, 70% for liver and 72% for muscle.
[d]Slope = y/x; x = μg/g feed (DW); y = μg/g tissue (DW).
[e] = A general toxicosis was observed in treatment group due to high proportion (50%) of sludge in diet.
[f]NS = Tissue concentration not significantly increased.
[g]NR = Not reported.

TABLE 4-5. TOXICITY OF NICKEL TO SOIL BIOTA

| Species | Chemical Form Applied | Soil pH | Soil Concentration (µg/g DW) | Application Rate (kg/ha) | Duration | Effects | References |
|---|---|---|---|---|---|---|---|
| Agricultural soil microorganisms | Coal fly ash | 6.5 | 25 | 50 | 37 days | No adverse effect on $CO_2$ evolution | Arthur et al., 1984 (p. 212) |
| | | | 100 | 200 | 37 days | $CO_2$ evolution reduced 15% | |
| | | | 100 | 350 | 37 days | $CO_2$ evolution reduced 24% | |

[a] Effect not necessarily due to nickel, since fly ash was applied.

TABLE 4-6. UPTAKE OF NICKEL BY SOIL BIOTA

| Species | Chemical Form | Soil Concentration Range (N)[a] (μg/g DW) | Tissue Analyzed | Control Tissue Concentration (μg/g DW) | Uptake Slope[b] | Reference |
|---|---|---|---|---|---|---|
| Earthworms | soils near highway | 12.7-25.1 (5) | whole body | 13 | 1.17[c] | Gish and Christensen, 1973 (p. 1061) |

[a] N = Number of soil concentrations, including control.
[b] y/x: = x = soil concentration; y = tissue concentration.
[c] Mean slope for two locations.

## SECTION 5

## REFERENCES


Abramowitz, M., and I. A. Stegun. 1972. Handbook of Mathematical Functions. Dover Publications, New York, NY.

American Conference of Governmental and Industrial Hygienists. 1980. Documentation of the Threshold Limit Values, 4th ed. Cincinnati, OH.

American Conference of Governmental and Industrial Hygienists. 1981. Threshold Limit Values for Chemical Substances and Physical Agents in the Working Environment with Intended Changes for 1981. Cincinnati, OH.

Allaway, W. H. 1968. Agronomic Controls Over the Environmental Cycling of Trace Elements. In: Norman, A. G. (ed.), Advances in Agronomy, Academic Press, New York, NY.

Ambrose, P., P. S. Larson, J. F. Borzelleca, and G. R. Henningar, Jr. 1976. Long-Term Toxicologic Assessment of Nickel in Rats and Dogs. J. Food Sci. Technol. 13:181.

Arthur, M. F., T. C. Zwick, D. A. Tolle, and P. Van Voris. 1984. Effects of Fly Ash on Microbial $CO_2$ Evolution from an Agricultural Soil. Water Air Soil Pollut. 22:209-216.

Bertrand, J. E., M. C. Lutrick, G. T. Edds, and R. L. West. 1981. Metal Residues in Tissues, Animal Performance and Carcass Quality with Beef Steers Grazing Pensacola Bahiagrass Pastures Treated with Liquid Digested Sludge. J. Ani. Sci. 53:1.

Bolton, J. 1975. Liming Effects on the Toxicity to Perennial Ryegrass of a Sewage Sludge Contaminated with Zinc, Nickel, Copper and Chromium. Environ. Pollut. 9:295-304.

Booz Allen and Hamilton, Inc. 1983. A Background Document on Cadmium in Municipal Sewage Sludge. Revised Draft. Prepared for U.S. Environmental Protection Agency Sludge Task Force. April 29.

Boswell, F. C. 1975. Municipal Sewage Sludge and Selected Element Applications to Soil: Effect on Soil and Fescue. J. Environ. Qual. 4(2):267-273.

Boyd, J. N., G. S. Stoewsand, J. G. Babish, J. N. Telford, and D. Lisk. 1982. Safety Evaluation of Vegetables Cultured on Municipal Sewage Sludge-Amended Soil. Arch. Environ. Contam. Toxicol. 11:399-405.

Boyer, K. W., J. W. Jones, S. K. Linscott, W. Wright, W. Stroube, and W. Cummingham. 1981. Trace Element Levels in Tissues from Cattle Fed a Sewage Sludge-Amended Diet. J. Toxicol. Environ. Health. 8:281-295.

Bray, B. J., R. D. Goodrich, R. H. Dowdy, and J. C. Meske. 1981. Performance and Tissue Mineral Contents of Lambs Fed Corn Silage Grown on Sludge-Amended Soils (Abstract only). J. Ani. Sci. 53:384-385.

Camp Dresser and McKee, Inc. 1983. New York City Special Permit Application-Ocean Disposal of Sewage Sludge. Prepared for the City of New York Department of Environmental Protection.

Camp Dresser and McKee, Inc. 1984. Development of Methodologies for Evaluating Permissible Contaminant Levels in Municipal Wastewater Sludges. Draft. Office of Water Regulations and Standards, U.S. Environmental Protection Agency, Washington, D.C.

Council for Agricultural Science and Technology. 1976. Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals. EPA 430/9-76-013.

Centers for Disease Control. 1983. NIOSH Recommendations for Occupational Health Standards. Morbid. Mortal. Weekly Rep. 32:7S-22S.

Chaney, R. L., and C. A. Lloyd. 1979. Adherence of Spray-Applied Liquid Digested Sewage Sludge to Tall Fescue. J. Environ. Qual. 8(3):407-411.

Chaney, R. L., S. B. Sterret, M. C. Morella, and C. A. Lloyd. 1982. Effect of Sludge Quality and Rate, Soil pH, and Time on Heavy Metal Residues in Leafy Vegetables. In: Proc. Fifth Annual Madison Conf. Applied Research and Practice on Municipal and Industrial Waste. University of Wisconsin, Madison.

Cunningham, J. D., D. R. Keeney, and J. A. Ryan. 1975a. Yield and Metal Composition of Corn and Rye Grown on Sewage Sludge-Amended Soil. J. Environ. Qual. 4:455-460.

Cunningham, J. D., D. R. Keeney, and J. A. Ryan. 1975b. Phytotoxicity in and Metal Uptake from Soil Treated with Metal-Amended Sewage Sludge. J. Environ. Qual. 4:455-460.

Duncomb, D. R., W. E. Larson, C. E. Clapp, R. H. Dowdy, D. R. Linden, and W. K. Johnson. 1982. Effect of Liquid Wastewater Sludge Application on Crop Yield and Water Quality. Process Design. p. 1185-1193.

Donigian, A. S. 1985. Personal Communication. Anderson-Nichols & Co., Inc., Palo Alto, CA. May.

Farrell, J. B., and H. Wall. 1981. Air Pollutional Discharges from Ten Sewage Sludge Incinerators. Draft Review Copy. U.S. Environmental Protection Agency, Cincinnati, OH. February.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, NJ.

Furr, A. K., T. F. Parkinson, T. Wachs et al. 1979. Multi-Element Analysis of Municipal Sewage Sludge Ashes. Absorption of Elements by Cabbage Grown in Sludge Ash-Soil Mixture. Environ. Sci. Technol. 13:1503-1506.

Furr, A. K., T. F. Parkinson, D. C. Elfving et al. 1981. Element Content of Vegetables and Apple Trees Grown on Syracuse Sludge-Amended Soils. J. Agric. Food Chem. 29:156-160.

Gelhar, L W., and C. J. Axness. 1981. Stochastic Analysis of Macrodispersion in 3-Dimensionally Heterogeneous Aquifers. Report No. H-8. Hydrologic Research Program, New Mexico Institute of Mining and Technology, Soccorro, NM.

Gerritse, R. G., R. Vriesema, J. W. Dalenberg, and H. P. DeRoos. 1982. Effect of Sewage Sludge on Trace Element Mobility in Soils. J. Environ. Qual. 2:359-363.

Gish, D. D., and R. E. Christensen. 1973. Cadmium, Nickel, Lead, and Zinc in Earthworms from Roadside Soil. Environ. Sci. Technol. 7(11):1060-1062.

Hem, J. D. 1970. Study and Interpretation of the Chemical Characteristics of Natural Water, Geological Survey Water Supply Paper 1473, U.S. Government Printing Office, Washington, D.C.

Hinesly, T. D., L. G. Hansen, and G. K. Dotson. 1984. Project Summary: Effects of Using Sewage Sludge on Agricultural and Disturbed Lands. EPA 600/S2-83-113. February.

Holmgren, G. 1983. Personal Communication. National Soil Survey Laboratory. Soil Conservation Service, USDA, Lincoln, NE.

International Agency for Research on Cancer. 1982. Chemicals, Industrial Processes and Industries Associated with Cancer in Humans. IARC Monographs Supplement 4 (Vol. 1-29). Lyon, France.

Kelling, K. A., D. R. Keeney, L. M. Walsh, and J. A. Ryan. 1977. A Field Study of the Agricultural Use of Sewage Sludge: III. Effect on Uptake and Extractability of Sludge-Borne Metals. J. Environ. Qual. 6(4):352-358.

Lisk, D. J., R. D. Boyd, J. N. Telford et al. 1982. Toxicologic Studies with Swine Fed Corn Grown on Municipal Sewage Sludge-Amended Soil. J. Anim. Sci. 55(3):613-619.

Logan, T. J., and R. H. Miller. 1983. Background Levels of Heavy Metals in Ohio Farm Soils. Research Circular 275. The Ohio State University Ohio Agricultural Research and Development Center. Wooster, OH.

Merck Index. 1976. Encyclopedia of Chemicals and Drugs, 9th Edition. Merck and Co., Inc., Rahway, NJ.

Mielke, H. W., J. C. Anderson, K. J. Berry, P. W. Mielke, R. L. Chaney, and M. Leech. 1983. Lead Concentration in Inner-City Soils as a Factor in the Child Lead Problem. Amer. J. Pub. Health. 73(12):1366-1369.

Miller, J., and F. C. Boswell. 1979. Mineral Content of Selected Tissues and Feces of Rats Fed Turnip Greens Grown on Soil Treated with Sewage Sludge. J. Agric. Food Chem. 27:1361-1365.

Mitchell, G. A., F. T. Bingham, and A. L. Page. 1978. Yield and Metal Composition of Lettuce and Wheat Grown on Soils Amended with Sewage Sludge Enriched with Cadmium, Copper, Nickel and Zinc. J. Environ. Qual. 7:165-171.

Narwal, R. P., B. R. Singh, and A. R. Panhwar. 1983. Plant Availability of Heavy Metals in a Sludge-Treated Soil: I. Effect of Sewage Sludge and Soil pH on the Yield and Chemical Composition of Rape. J. Environ. Qual. 12(3):358-365.

National Academy of Sciences. 1980. Mineral Tolerances of Domestic Animals. NAS Subcommittee on Mineral Toxicity in Animals, Washington, D.C.

O'Dell, G. D., W. J. Miller, S. L. Moore and W. A. King. 1970. Effect of Nickel as the Chloride and the Carbonate on Palatability of Cattle Feed. J. D. Dairy Sci. 53:1266.

Osuna, O., G. T. Edds, and J. A. Popp. 1981. Comparative Toxicity of Feeding Dried Urban Sludge and an Equivalent Amount of Cadmium to Swine. Am. J. Vet. Res. 42:1542-1546.

Pennington, J. A. T. 1983. Revision of the Total Diet Study Food Lists and Diets. J. Am. Diet. Assoc. 82:166-173.

Pettyjohn, W. A., D. C. Kent, T. A. Prickett, H. E. LeGrand, and F. E. Witz. 1982. Methods for the Prediction of Leachate Plume Migration and Mixing. U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, OH.

Phatak, S. S., and V. N. Patwardhan. 1950. Toxicity of Nickel. J. Sci. Ind. Res. 98(3):70.

Pierce, F. J., R. H. Dowdy, and D. F. Grigal. 1982. Concentrations of Six Trace Metals in Some Major Minnesota Soil Series. J. Environ. Qual. 11(3):416-422.

Ryan, J. A., H. R. Pahren, and J. B. Lucas. 1982. Controlling Cadmium in the Human Food Chain: A Review and Rationale Based on Health Effects. Environ. Res. 28:251-302.

Schroeder, H. A., and M. Mitchener. 1971. Toxic Effects of Trace Elements on Their Reproduction of Mice Rats. Arch. Environ. Health. 23:102.

Schroeder, H. A., W. H. Vinton, Jr., and J. J. Balassa. 1963. Effects of Chromium, Cadmium, and Other Trace Metals on the Growth and Survival of Mice. J. Nutr. 80:39.

Schroeder, H. A., W. H. Vinton, Jr., and J. J. Balassa. 1964. Chromium, Lead, Cadmium, Nickel and Titanium in Mice: Effect on Mortality, Tumors, and Tissue Levels. J. Nutr. 83:239.

Schroeder, H. A., M. Mitchener and A. P. Nason. 1974. Life-Term Effects of Nickel in Rats: Survival, Tumors, Interactions with Trace Elements and Tissue Levels. J. Nutr. 104:239.

Sikora, L. J., W. D. Burge, and J. E. Jones. 1982. Monitoring of a Municipal Sludge Entrenchment Site. J. Environ. Qual. 2(2):321-325.

Telford, J. N., M. L. Thonney, D. E. Hogue et al. 1982. Toxicologic Studies in Growing Sheep Fed Silage Corn Cultured on Municipal Sludge-Amended Acid Subsoil. J. Toxicol. Environ. Health. 10:73-85.

Thornton, I., and P. Abrams. 1983. Soil Ingestion - A Major Pathway of Heavy Metals into Livestock Grazing Contaminated Land. Sci. Total Environ. 28:287-294.

U.S. Department of Agriculture. 1975. Composition of Foods. Agricultural Handbook No. 8.

U.S. Environmental Protection Agency. 1977. Environmental Assessment of Subsurface Disposal of Municipal Wastewater Sludge: Interim Report. EPA/530/SW-547. Municipal Environmental Research Laboratory, Cincinnatti, OH.

U.S. Environmental Protection Agency. 1979a. Air Quality Data for Metals 1976 from the National Air Surveillance Networks. EPA 600/4-79-054. Environmental Monitoring and Support Laboratory, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 1979b. Industrial Source Complex (ISC) Dispersion Model User Guide. EPA 450/4-79-30. Vol. 1. Office of Air Quality Planning and Standards, Research Triangle Park, NC. December.

U.S. Environmental Protection Agency. 1980. Ambient Water Quality Criteria for Nickel. EPA 440/5-80-060. Office of Water Regulations and Standards, Washington, D.C.

U.S. Environmental Protection Agency. 1982a. Fate of Priority Pollutants in Publicly-Owned Treatment Works. Final Report. Vol. I. EPA 440/1-82-303. Effluent Guidelines Division, Washington, D.C. September.

U.S. Environmental Protection Agency. 1982b. Errata for Ambient Water Quality Criteria Documents. Environmental Criteria and Assessment Office, Cincinnati, OH. February 23.

U.S. Environmental Protection Agency. 1983a. Assessment of Human Exposure to Arsenic: Tacoma, Washington. Internal Document. OHEA-E-075-U. Office of Health and Environmental Assessment, Washington, D.C. July 19.

U.S. Environmental Protection Agency. 1983b. Health Assessment Document for Nickel. External Review Draft. EPA 600/8-83-012. Office of Health and Environmental Assessment, Washington, D.C.

U.S. Environmental Protection Agency. 1983c. Rapid Assessment of Potential Groundwater Contamination Under Emergency Response Conditions. EPA 600/8-83-030.

U.S. Environmental Protection Agency. 1984. Air Quality Criteria for Lead. External Review Draft. EPA 600/8-83-028B. Environmental Criteria and Assessment Office, Research Triangle Park, NC. September.

U.S. Environemental Protection Agency. 1985. Drinking Water Criteria Document for Nickel. ECAO-Cin-443. Environmental Criteria and Assessment Office, Cincinnati, OH. March.

Valdares, J.M.A.S., M. Gal, U. Mingelgrin, and A. L. Page. 1983. Some Heavy Metals in Soils Treated with Sewage Sludge, Their Effects on Yield, and Their Uptake by Plants. J. Environ. Qual. 12:49-57.

Webber, J. 1972. Effects of Toxic Metals in Sewage on Crops. Water Pollut. Control. p. 404-410.

Weber, C. W., and B. L. Reid. 1968. Nickel Toxicity in Growing Chicks. J. Nutr. 95:612.

Weber, C. W., and B. L. Reid. 1969. Nickel Toxicity in Young Growing Mice. J. Anim. Sci. 28:620.

Whanger, P. D. 1973. Effects of Dietary Nickel on Enzyme Activities and Mineral Content in Rats. Toxicol. Appl. Pharmacol. 25:323.

**APPENDIX**

# PRELIMINARY HAZARD INDEX CALCULATIONS FOR NICKEL IN MUNICIPAL SEWAGE SLUDGE

## I. LANDSPREADING AND DISTRIBUTION-AND-MARKETING

### A. Effect on Soil Concentration of Nickel

#### 1. Index of Soil Concentration Increment (Index 1)

a. Formula

$$\text{Index 1} = \frac{(SC \times AR) + (BS \times MS)}{BS\ (AR + MS)}$$

where:

SC = Sludge concentration of pollutant (μg/g DW)
AR = Sludge application rate (mt DW/ha)
BS = Background concentration of pollutant in soil (μg/g DW)
MS = 2000 mt DW/ha = Assumed mass of soil in upper 15 cm

b. Sample calculation

$$1.0 = \frac{(44.7\ \mu g/g\ DW \times 5\ mt/ha) + (18.6\ \mu g/g\ DW \times 2000\ mt/ha)}{18.6\ \mu g/g\ DW\ (5\ mt/ha + 2000\ mt/ha)}$$

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

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

a. Formula

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

where:

$I_1$ = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in 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**

$$\text{Index 3} = \frac{(I_1 - 1)(BS \times UB) + BB}{TR}$$

where:

$I_1$ = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
UB = Uptake slope of pollutant in soil biota (μg/g tissue DW [μg/g soil DW]$^{-1}$)
BB = Background concentration in soil biota (μg/g DW)
TR = Feed concentration toxic to predator (μg/g DW)

b. **Sample calculation**

$$0.044 = [(1.0 - 1)\ (18.6\ \mu g/g\ DW \times 1.17\ \mu g/g\ DW\ [\mu g/g\ soil\ DW]^{-1}) + 13\ \mu g/g\ DW] \div 300\ \mu g/g\ DW$$

C. **Effect on Plants and Plant Tissue Concentration**

1. **Index of Phytotoxicity (Index 4)**

a. **Formula**

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

where:

$I_1$ = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
TP = Soil concentration toxic to plants (μg/g DW)

b. **Sample calculation**

$$0.37 = \frac{1.0 \times 18.6\ \mu g/g\ DW}{50\ \mu g/g\ DW}$$

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

a. **Formula**

$$\text{Index 5} = \frac{(I_1 - 1) \times BS}{BP} \times CO \times UP + 1$$

where:

$I_1$ = Index 1 = Index of soil concentration increment (unitless)
BS = Background concentration of pollutant in soil (μg/g DW)
CO = 2 kg/ha $(\mu g/g)^{-1}$ = Conversion factor between soil concentration and application rate
UP = Uptake slope of pollutant in plant tissue (μg/g tissue DW $[kg/ha]^{-1}$)
BP = Background concentration in plant tissue (μg/g DW)

b. **Sample calculation**

$$1.0 = \frac{(1.0 - 1) \times 18.6\ \mu g/g\ DW}{1.7\ \mu g/g\ DW} \times \frac{2\ kg/ha}{\mu g/g\ soil}$$

$$\times \frac{0.8\ \mu g/g\ tissue}{kg/ha} + 1$$

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

a. **Formula**

$$\text{Index 6} = \frac{PP}{BP}$$

where:

PP = Maximum plant tissue concentration associated with phytotoxicity (μg/g DW)
BP = Background concentration in plant tissue (μg/g DW)

b. **Sample calculation**

$$16 = \frac{160\ \mu g/g\ DW}{10\ \mu g/g\ DW}$$

## C. Effect on Herbivorous Animals

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

a. **Formula**

$$\text{Index 7} = \frac{I_5 \times BP}{TA}$$

where:

$I_5$ = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
TA = Feed concentration toxic to herbivorous animal (μg/g DW)

b. **Sample calculation**

$$0.0090 = \frac{1.0 \times 0.9\ \mu g/g\ DW}{100\ \mu g/g\ DW}$$

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

a. **Formula**

$$\text{If } AR = 0, \quad I_8 = \frac{BS \times GS}{TA}$$

$$\text{If } AR \neq 0, \quad I_8 = \frac{SC \times GS}{TA}$$

where:

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

b. **Sample calculation**

$$\text{If AR} = 0, \quad 0.0093 = \frac{18.6\ \mu g/g\ DW \times 0.05}{100\ \mu g/g\ DW}$$

$$\text{If AR} \neq 0, \quad 0.022 = \frac{44.7\ \mu g/g\ DW \times 0.05}{100\ \mu g/g\ DW}$$

## E. Effect on Humans

### 1. Index of Human Toxicity Resulting from Plant Consumption (Index 9)

a. **Formula**

$$\text{Index 9} = \frac{[(I_5 - 1)\ BP \times DT] + DI}{ADI}$$

where:

$I_5$ = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (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)
ADI = Acceptable daily intake of pollutant (μg/day)

b. **Sample calculation (toddler)**

$$0.041 = \frac{[(1.1 - 1) \times 1.7\ \mu g/g\ DW \times 74.5\ g/day] + 135\ \mu g/day}{3500\ \mu g/day}$$

### 2. Index of Human Toxicity Resulting from Consumption of Animal Products Derived from Animals Feeding on Plants (Index 10)

a. **Formula**

$$\text{Index 10} = \frac{[(I_5 - 1)\ BP \times UA \times DA] + DI}{ADI}$$

where:

$I_5$ = Index 5 = Index of plant concentration increment caused by uptake (unitless)
BP = Background concentration in plant tissue (μg/g DW)
UA = Uptake slope of pollutant in animal tissue (μg/g tissue DW $[\mu g/g$ feed $DW]^{-1}$)

DA = Daily human dietary intake of affected animal tissue (g/day DW)

DI = Average daily human dietary intake of pollutant (μg/day)

ADI = Acceptable daily intake of pollutant (μg/day)

**b. Sample calculation (toddler)**

$$.039 = \frac{[(1.1-1) \times 0.9\ \mu g/g\ DW \times 0.024\ \mu g/g\ tissue[\mu g/g\ feed]^{-1} \times 0.97\ g/day] + 135\ \mu g/day}{3500\ \mu g/day}$$

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

**a. Formula**

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

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

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 (unitless)

UA = Uptake slope of pollutant in animal tissue (μg/g tissue DW [μg/g feed $DW^{-1}$]

DA = Average daily human dietary intake of affected animal tissue (g/day DW)

DI = Average daily human dietary intake of pollutant (μg/day)

ADI = Acceptable daily intake of pollutant (μg/day)

**b. Sample calculation (toddler)**

$$.039 = \frac{(44.7\ \mu g/g\ DW \times 0.05 \times 0.024\ \mu g/g\ tissue\ [\mu g/g\ feed]^{-1} \times 0.97\ g/day\ DW) + 135\ \mu g/day}{3500\ \mu g/day}$$

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

**a. Formula**

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

Pure sludge ingestion: $\text{Index 12} = \frac{(SC \times DS) + DI}{ADI}$

where:

$I_1$ = Index 1 = Index of soil concentration increment (unitless)
SC = Sludge concentration of pollutant (µg/g DW)
BS = Background concentration of pollutant in soil (µg/g DW)
DS = Assumed amount of soil in human diet (g/day)
DI = Average daily dietary intake of pollutant (µg/day)
ADI = Acceptable daily intake of pollutant (µg/day)

b. **Sample calculation (toddler)**

$$0.065 = \frac{(1.0 \times 18.6\ \mu g/g\ DW \times 5\ g\ soil/day) + 135\ \mu g/day}{3500\ \mu g/day}$$

Pure sludge:

$$0.10 = \frac{(44.7\ \mu g/g\ DW \times 5\ g\ soil/day) + 135\ \mu g/day}{3500\ \mu g/day}$$

5. **Index of Aggregate Human Toxicity (Index 13)**

a. **Formula**

$$\text{Index 13} = I_9 + I_{10} + I_{11} + I_{12} - \frac{3DI}{ADI}$$

where:

$I_9$ = Index 9 = Index of human toxicity resulting from plant consumption (unitless)
$I_{10}$ = Index 10 = Index of human toxicity resulting from consumption of animal products derived from animals feeding on plants (unitless)
$I_{11}$ = Index 11 = Index of human toxicity resulting from consumption of animal products derived from animals ingesting soil (unitless)
$I_{12}$ = Index 12 = Index of human toxicity resulting from soil ingestion (unitless)
DI = Average daily dietary intake of pollutant (µg/day)
ADI = Acceptable daily intake of pollutant (µg/day)

b. **Sample calculation (toddler)**

$$0.067 = (0.041 + 0.039 + 0.039 + 0.065) - \left(\frac{3 \times 135\ \mu g/day}{3500\ \mu g/day}\right)$$

# 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, 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

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

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

where:

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

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

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

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

and where for the unsaturated zone:

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

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

PS = Percent solids (by weight) of landfilled sludge = 20%
t = Time (years)
$\chi$ = h = Depth to groundwater (m)
$D^*$ = $\alpha \times V^*$ ($m^2$/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)
$K_d$ = Soil sorption coefficient (mL/g)

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

$\mu$ = 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)
$\chi$ = $\Delta \ell$ = Distance from well to landfill (m)
$D^*$ = $\alpha \times V^*$ ($m^2$/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 $K_d$ 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:

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

**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 Increment Resulting from Landfilled Sludge (Index 1)**

**1. Formula**

$$\text{Index 1} = \frac{C_{max} + BC}{BC}$$

where:

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

2. **Sample Calculation**

$$1.25 = \frac{1.22\ \mu g/L + 4.8\ \mu g/L}{4.8\ \mu g/L}$$

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

1. **Formula**

$$\text{Index 2} = \frac{[(I_1 - 1)\ BC \times AC] + DI}{ADI}$$

where:

$I_1$ = Index 1 = Index of groundwater concentration increment resulting from landfilled sludge
BC = Background concentration of pollutant in groundwater (μg/L)
AC = Average human consumption of drinking water (L/day)
DI = Average daily human dietary intake of pollutant (μg/day)
ADI = Acceptable daily intake of pollutant (μg/day)

2. **Sample Calculation**

$$0.115 = \frac{[(1.25 - 1) \times 4.8\ \mu g/L \times 2\ L/day] + 400\ \mu g/day}{3500\ \mu g/day}$$

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**

$1.0 = [(2.78 \times 10^{-7}$ hr/sec x g/mg x 2660 kg/hr DW x 44.7 mg/kg DW 0.002 x 3.4 μg/$m^3$) + 0.009 μg/$m^3$] ÷ 0.009 μg/$m^3$

B. **Index of Human Toxicity/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 (μg/$m^3$)
EC = Exposure criterion (μg/$m^3$)

2. **Sample Calculation**

$$3.0 = \frac{[(1.0 - 1) \times 0.009 \ \mu g/m^3] + 0.009 \ \mu g/m^3}{0.00304 \ \mu g/m^3}$$

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) | [T] | [W] | [T] | [T] | [T] | [T] | [W] | N[a] |
| Unsaturated zone | 44.7 | 662.7 | 44.7 | 44.7 | 44.7 | 44.7 | 662.7 | |
| 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 |
| Soil sorption coefficient, $K_d$ (mL/g) | 58.6 | 58.6 | 12.2 | NA | 58.6 | 58.6 | 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) | 11200 | 166000 | 11200 | 11200 | 11200 | 11200 | 166000 | N |
| Peak concentration, $C_u$ (μg/L) | 111 | 1640 | 422 | 11200 | 111 | 111 | 166000 | N |
| Pulse duration, $t_o$ (years) | 504 | 504 | 132 | 5.00 | 504 | 504 | 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) | 111 | 1640 | 422 | 11200 | 111 | 111 | 166000 | N |
| Saturated zone assessment (Equations 1 and 3) | | | | | | | | |
| Maximum well concentration, $C_{max}$ (μg/L) | 1.22 | 18.0 | 1.22 | 1.21 | 6.46 | 45.6 | 3830 | N |
| Index of groundwater concentration increment resulting from landfilled sludge, Index 1 (unitless) (Equation 4) | 1.25 | 4.76 | 1.25 | 1.25 | 2.35 | 10.5 | 800 | 0 |
| Index of human toxicity resulting from groundwater contamination, Index 2 (unitless) (Equation 5) | 0.115 | 0.125 | 0.115 | 0.115 | 0.118 | 0.140 | 2.31 | 0.114 |

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