Technical Report


Variation of Heavy Metals
Concentrations in Municipal
Sludge and Sludge Compost
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ABSTRACT

The purpose of this research was to examine the variation of heavy metals concentrations in municipal sludge and sludge compost. The variation was examined within a wastewater treatment plant to determine the fate of metals during sludge treatment and disposal.

The research was completed in two parts. First, a detailed literature review was completed to examine the sources of heavy metals in wastewater and their fate during treatment. Next, a field study was conducted at an existing wastewater treatment plant practicing sludge composting in Williamstown, Massachusetts.

A sampling and analysis program was devised to measure the concentrations of cadmium, chromium, copper, nickel, lead and zinc in the solids stream of the plant. Concentrations of these metals were measured in the sludge before and after composting, and in compost stored on site.

The results were that the concentrations of cadmium, chromium, lead and zinc were typically higher in the compost than the parent sludge. Concentrations of copper and nickel were typically lower in the compost than in the sludge. Statistical analysis of the data indicated that these differences were significant.

Cadmium, copper, nickel and zinc were detected in the filtrate from the sludge dewatering and in the leachate from the

compost piles. The source of the cadmium and zinc were not determined. The copper and zinc were apparently displaced from the sludge during lime conditioning.

Variability of the metals concentrations during the study period in the sludge, batch compost and stored compost were different for different metals. The difference between metals concentrations in batch compost and stored compost samples varied depending on the metal studied and the difference in age between the two sample types.

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CHAPTER I

INTRODUCTION

Heavy metals can cause several problems in municipal
wastewater treatment systems. High concentrations of metals in
wastewater are toxic to biological treatment processes. Metals
discharged in the treated effluent can cause environmental damage.
Metals in wastewater sludges can be damaging to the environment as
well.

Biological treatment processes remove metals from the liquid
stream and concentrate them in the solid stream. Heavy metals
which cannot be detected in the influent wastewater can be
concentrated to measurable levels in the sludge (EPA, 1979b).
Metals levels in the sludge may be three to four orders of
magnitude higher than in the influent wastewater (Olthof and
Lancy, 1978). In the past, this effect has been considered
totally beneficial since it removed the metals from the treated
wastewater. Sludge disposal was typically by incineration or
landfilling, neither of which was limited by the metals content of
the sludge.

In recent years, restrictions on incineration of wastes and
decreases in available landfill space along with increasing
disposal costs have limited sludge disposal options for many

cities and towns. As a result, many municipalities are seeking alternative methods of sludge disposal.

One alternative method of disposal being employed is land application of sludge. Sludge is applied to land as a fertilizer or soil conditioner. Land application of sludge may be used for agricultural, forestry, nursery, or turf crops; reclamation of severely disturbed land; or for recreational or roadside land development.

In many areas, particularly in the Northeast, there is insufficient land available for sludge application. As a result, some municipalities are considering composting the sludge prior to disposal. Currently in Massachusetts there are 23 composting facilities either in operation or under development (Goldstein, 1987).

Composting is an aerobic biological stabilization process carried out at thermophilic temperatures resulting from biological activity. This process converts the sludge into a stable, dry, inoffensive humus-like material (Haug, 1980).

Composted sludge, like raw sludge, may be disposed of by land application. Composting sludge, however, has a number of advantages. Composted sludge has a lower moisture content, less volume, and is more stable than raw sludge. Composted sludge is easier to store, handle, and transport than raw sludge. Composted sludge has fewer pathogens and less odor than raw sludge making it more suitable for sale and distribution to individual users as a

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soil amendment. These advantages increase the number of available disposal options. Composted sludge may also be used as landfill cover (Parr, et al., 1978, EPA, 1979b).

Most states and the federal government regulate land disposal of sludge and composted sludge primarily on the basis of it's heavy metals content. Massachusetts regulations (310 CMR 32) control disposal based on the concentrations of cadmium, chromium, copper, mercury, nickel, lead, zinc, boron, and molybdenum in the sludge or compost. These restrictions limit available disposal sites and create higher land requirements for sludge disposal.

When evaluating the feasibility of sludge composting, the metals content of the final product is an important parameter. Typically, initial predictions of final metals concentrations are based on rules of thumb and limited data from previous projects. There is little information in the literature examining the factors affecting the fate of heavy metals during composting.

This study was undertaken to examine and quantify the variations in heavy metals content of municipal sludge and sludge compost. This objective was accomplished in two steps. First, a detailed literature review was completed examining information or collected data on heavy metals in wastewater and wastewater sludges. The specific topics addressed were:

1. Which metals are typically found in wastewaters and sludges and at what concentrations?

2. What are the sources of the metals?

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3. What factors affect the incorporation of the
   metals into the sludge?

4. What are the potential environmental impacts of
   the metals as a result of land disposal of sludge?

5. What options are available to deal with the problems
   caused by metals in sludge?

The second step was to perform a field study of an operating
sludge composting facility. The objective of this study was to
produce a statistically sound database of the change in sludge
metals concentrations as a result of composting. Once sufficient
data are available documenting the effect of composting on metals
concentrations, future studies can examine the specific processes
involved.

A sampling program was designed to intensively sample and
analyze the sludge entering, and compost exiting the batch
composting process. The sampling and analysis were done to
accurately characterize the quality of each batch of sludge,
before and after composting. Statistical analysis of the data was
performed to provide further support for the validity of the
results.

Six heavy metals were selected for analysis: cadmium,
chromium, copper, nickel, lead and zinc. These metals are present
in measurable quantities in all municipal sludges. They are also
included in most states' regulations on land application of
sludge.

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CHAPTER II


LITERATURE REVIEW


## 2.1  METALS IN MUNICIPAL WASTEWATER TREATMENT PLANTS


### 2.1.1  Typical Levels and Variability: Wastewater and Sludges

A number of studies have been conducted to characterize the composition of municipal wastewaters (Brown et al., 1973, Klein et al., 1974,  Gurnham et al., 1979, Lester et al., 1979, Stoveland et al., 1979, Hanley, 1985, Aulenbach et al., 1987), POTW effluents (Brown et al., 1973, Klein et al., 1974, Lester et al., 1979, Stoveland et al., 1979, Aulenbach et al., 1987), and municipal sludges (Brown et al., 1973, Bastian and Whittington, 1976, Sommers et al., 1976, Sommers, 1977, Olthof and Lancy, 1978, Sterritt and Lester, 1981a, Hanley, 1985).  The elements selected for analysis differed from study to study, but certain ones were common to all studies.  Furr et al. (1976) and Mumma et al. (1984) conducted the most detailed studies of metals in sludge.  Furr et al. analyzed sludge from 16 cities for 68 elements.  Mumma et al. analyzed 30 sewage sludges for 59 elements.

While individual values vary widely, mean values for metals in sludge are more constant.  EPA (1982) sampled 50 treatment plants 24 hours a day for at least six days, measuring the levels of priority pollutants in the influent, effluent and sludge.

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Fricke et al. (1985) compared the mean values in sludge from this study with those from other available municipal sludge data bases. The values obtained by EPA for metals in sludge were within approximately a factor of two of the database values.

Olthof et al. (1978) studied literature values for metals' levels in wastewater treatment processes. They developed accumulation factors for metals in sludge. These are ratios of metals in sludge to metals removed from wastewater (expressed as mg metal/kg dry wt sludge per mg/liter metal removed from the wastewater). Values obtained ranged from 3270 to 24700. Digested sludge had higher values than raw sludge. They concluded that as a rule of thumb, 10,000 was a reasonable estimate.

Table 1 presents some typical values from the literature for the composition of raw wastewater and treated effluent. Table 2 presents ranges of metals' levels measured in sludges. The variability in metal content of sludges from city to city is a reflection of the variability of sources of metals entering the treatment plants (Sommers et al., 1976). For an individual city, it is a function of influent concentration.

Sommers et al. (1976) examined the variability of the composition of sludge. The coefficient of variation (standard deviation as a percent of the mean) for the metals studied ranged from 32% to 72% for studies conducted within a city and from 77% to 146% for studies of variability between cities. According to

TABLE 1.  METAL CONCENTRATIONS IN WWTP INFLUENTS AND EFFLUENTS  (micrograms per liter)

| Reference | | Al | As | Be | Cd | Cr | Cu | Fe | Pb | Mn | Hg | Ni | Se | Ag | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hanley, 1985 | influent | 865 | -- | -- | 0 | 30 | 230 | 1600 | 70 | 170 | 0.4 | 20 | -- | 10 | 200 |
| | effluent | 200 | -- | -- | 0 | 10 | 65 | 290 | 40 | 95 | 0.1 | 0 | -- | 0 | 90 |
| Brown et al. 1973 | influent | -- | -- | -- | 18 | 59 | 170 | -- | 160 | -- | 0.6 | -- | -- | -- | 353 |
| | effluent | -- | -- | -- | 16 | 13 | 67 | -- | 92 | -- | 0.5 | -- | -- | -- | 182 |
| Yost and Wukasch, 1983 | influent | -- | -- | -- | 33 | 786 | 168 | 17300 | 51 | -- | -- | 115 | -- | -- | 2070 |
| | effluent | -- | -- | -- | 6.3 | 16.7 | 25.2 | 335 | 2.6 | -- | -- | 81.2 | -- | -- | 233 |
| Aulenbach et al., 1987 | influent | 2006 | 7.6 | 0.5 | 7.6 | 182 | 392 | -- | 872 | -- | 0.3 | 1000 | 10.8 | 23.4 | 580 |
| | effluent | 534 | 7.5 | -- | 0.9 | 18.6 | 65.5 | -- | 150 | -- | 0.2 | -- | 10.2 | 2.5 | 300 |

TABLE 2   RANGE OF METAL CONCENTRATIONS IN SLUDGE (ppm)

Reference

| Metal | Sommers (1977) Range | Avg | Solotto and Farrell (1972) Range | Avg | Bastian & Whittington (1976) Range | Avg |
|-------|-------|-----|-------|-----|-------|-----|
| Al | --- | --- | 7750-36000 | 17360 | --- | --- |
| As | 6-230 | 43 | --- | --- | 10-50 | 9 |
| Ba | --- | --- | 100-4010 | 1360 | nd-3000 | 1460 |
| Be | --- | --- | 1.2-6.5 | 2.5 | --- | --- |
| B | 4-760 | 77 | 3-1490 | 46 | 200-1430 | 430 |
| Cd | 3-3410 | 110 | 1-500 | 264 | nd-1100 | 87 |
| Cr | 10-99000 | 2620 | 100-11000 | 2280 | 22-30000 | 1800 |
| Co | 1-18 | 5.3 | --- | --- | nd-800 | 350 |
| Cu | 84-10400 | 1210 | 10-16000 | 1650 | 45-16030 | 1250 |
| Fe | --- | --- | 10900-60000 | 30650 | --- | --- |
| Pb | 13-19700 | 1360 | 180-7520 | 1890 | 80-2600 | 1940 |
| Mn | 18-7100 | 380 | 60-6040 | 976 | 100-8800 | 1190 |
| Hg | 0.5-10600 | 733 | --- | --- | 0.1-89 | 7 |
| Mo | 5-39 | 28 | 2-1290 | 254 | --- | --- |
| Ni | 2-3520 | 320 | 30-3000 | 372 | nd-2800 | 410 |
| Ag | --- | --- | 80-500 | 195 | nd-960 | 225 |
| Sr | --- | --- | --- | 260 | nd-2230 | 440 |
| Sn | --- | --- | 500-700 | 600 | --- | --- |
| Ti | --- | --- | 1000-20000 | 14200 | --- | --- |
| V | --- | --- | 320-10000 | 5200 | nd-2100 | 510 |
| Zn | 101-27800 | 2790 | 500-11000 | 4040 | 51-28360 | 3483 |
| Zr | --- | --- | 100-5000 | 2030 | --- | --- |

nd-not detected

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the studies conducted within individual cities, zinc, nickel, lead, and copper were moderately variable (C.V. 25-50%), while cadmium was highly variable (C.V.>50%). Doty et al. (1977) sampled six plants on a biweekly basis for one year. The coefficients of variation for the metals studied ranged from 21-47%.

Sommers et al. recommends sampling every two to three months for a year to characterize sludge composition prior to land application. Doty et al. concluded that three to five biweekly samples are sufficient. EPA (1983) recommends taking weekly samples for five weeks or more until the average value for the element being analyzed is within the 95 percent confidence interval.

## 2.1.2 Physical, Chemical and Biological Factors

Metals removal from wastewater and incorporation into sludge occurs primarily through two physicochemical processes: precipitation and adsorption. Settling processes dominate in primary treatment (Hanley, 1985). Metals removed in primary treatment are in the insoluble form or are adsorbed to organic solids or to iron or manganese oxyhydroxide particles (Oliver and Cosgrove, 1974). Soluble metals and metals associated with non-settleable particles are discharged to secondary treatment (activated sludge). In the activated sludge process, metals are removed in two ways. Particulate metals are enmeshed in the biological flocs and settled out. Metal ions in solution are

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adsorbed onto microbial surfaces or onto extracellular polymers produced by the microorganisms (Lester, 1983). Adsorption sites in the biomass may be surface hydroxyl groups (hexose and pentose molecules on neutral polysaccharides), surface carboxyl groups on anionic polymers (Stoveland and Lester, 1980), or phosphoryl, carboxyl, sulphydryl and hydroxyl groups of membrane proteins and lipids and of cell wall structural components (Nelson et al., 1981). Table 3 gives literature values for percent removal of metals by treatment process.

### 2.1.2.a PRIMARY TREATMENT

The factors that affect metal removal in primary treatment process are the efficiency of suspended solids removal and the chemical species of the metal. Suspended solids removal is affected by basin design, surface loading rate, flow rate and influent suspended solids concentration. The chemical species is dependent upon the metal concentration, COD (a measure of dissolved organic carbon), hardness, alkalinity and pH of the influent wastewater (Lester, 1983).

The percent removal of metals in primary treatment can vary widely temporally at a single plant. The ratio of day to night metal loading can be as high as 8:1. There is no evidence of correlation between influent concentration and percent removal except for cadmium. The percent removal of cadmium decreases at increased influent concentrations (Lester, 1983). Rossin et al.

TABLE 3.  PERCENT REMOVAL OF METALS BY UNIT PROCESS

| Reference | Al | Cd | Cr | Co | Cu | Fe | Pb | Hg | Mn | Ni | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Primary Treatment** | | | | | | | | | | | |
| Oliver and Cosgrove, 1974 | -- | 60 | 55 | 50 | 33 | 49 | 66 | 60 | 33 | 15 | 54 |
| Hanley, 1985 | 42 | -- | 17 | -- | 7 | 21 | 29 | 20 | 0 | 0 | 30 |
| Lester et al., 1979 | -- | 72 | -- | -- | 70 | -- | 73 | -- | -- | -- | -- |
| Stoveland et al., 1979 | -- | -- | 51 | -- | -- | -- | -- | -- | -- | 23 | 74 |
| Brown et al., 1973 | -- | 25 | 36 | -- | 70 | -- | 59 | 54 | -- | -- | 68 |
| Hannah et al., 1986 | -- | 12 | 7 | -- | 19 | -- | 30 | -- | -- | 4 | -- |
| **Activated Sludge** | | | | | | | | | | | |
| Oliver and Cosgrove, 1974 | -- | 50 | 54 | -- | 60 | -- | 79 | -- | -- | 1 | 50 |
| Hanley, 1985 | 84 | -- | 99 | -- | 82 | 74 | 67 | 94 | 29 | 55 | 60 |
| Lester et al., 1979 | -- | 63 | -- | -- | 79 | -- | 73 | -- | -- | -- | -- |
| Stoveland et al., 1979 | -- | -- | 33 | -- | -- | -- | -- | -- | -- | 61 | 78 |
| Brown et al., 1973 | -- | 11 | 78 | -- | 61 | -- | 43 | -- | -- | -- | 48 |
| Hannah et al., 1986 | -- | 24 | 82 | -- | 82 | -- | 65 | -- | -- | 43 | -- |
| **Trickling Filter** | | | | | | | | | | | |
| Hanley, 1985 | 55 | -- | 33 | -- | 32 | 60 | 14 | 41 | 17 | 73 | 33 |
| Hannah et al., 1986 | -- | 28 | 52 | -- | 60 | -- | 48 | -- | -- | 30 | -- |
| **Extended Aeration** | | | | | | | | | | | |
| Hanley, 1985 | 70 | -- | 77 | -- | 82 | 72 | 40 | 37 | 28 | 50 | 39 |
| **Aerated Lagoon** | | | | | | | | | | | |
| Hannah et al., 1986 | -- | -- | 71 | -- | 74 | -- | 58 | -- | -- | 35 | -- |

(1983) found that at a constant influent metal concentration the percent removal of cadmium, chromium, copper and zinc decreased as flow rate increased. Removal of lead was higher at higher flow rates. Brown et al. (1973) found that percent removal decreased when digester liquor was recirculated through primary treatment. According to Lester (1983), the order of removal in primary treatment, on average, is Pb>Cu>Zn>Cd>Cr>Ni.

## 2.1.2.b SECONDARY TREATMENT

In secondary treatment uptake of metals by the biomass occurs in two stages. Rapid uptake of metals occurs in the first three to ten minutes. During this stage large amounts of metals are adsorbed by the biomass (Chen et al., 1974, Nelson et al., 1981). The second stage is a period of slow, continous uptake. During the second stage, almost complete equilibrium between the adsorbed metals and metals in solution is approached after three hours. Complete equilibrium is achieved after approximately two weeks (Nelson et al., 1981).

Several studies have found a correlation between the concentration of some metals in the influent to the activated sludge process and the amount of those metals removed in the sludge. This relationship can be fitted to Freundlich or Langmuir isotherms (Neufeld and Hermann, 1975, Gould and Genetelli, 1978, Nelson et al., 1981, Sterritt et al., 1981).

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Metal removal by activated sludge varies widely between treatment plants as well as for different metals. Values in the literature for metal removal range from 1 to 82% (Oliver and Cosgrove, 1974, Nelson et al., 1981, Hannah et al., 1986). Brown and Lester (1979) divided the factors which influence metal removal into three groups: process parameters, physical/chemical factors and biological factors. Process parameters are sludge volume index, sludge age, suspended solids removal, dissolved oxygen concentration and settling time. Physical/chemical factors are temperature, pH, metal ion concentration, metal solubility, metal valency, concentration of complexing agents and particle size. The biological factor is the concentration of extracellular polymers. Sterritt et al. (1981) state that sludge volume index, MLSS, effluent suspended solids and effluent COD affect metal removal. In the activated sludge process these are all a function of sludge age. Nelson et al. (1981) concluded that system pH is the single most important factor influencing chemical speciation of metals and their distribution between bacterial solids and solution phases.

Several studies have examined the effect of sludge age on metal removal by activated sludge (Nelson et al., 1981, Sterritt et al., 1981, Sterritt and Lester, 1981b, Rossin et al., 1982). In general, metal uptake by the sludge increases with sludge age . Maximum uptake occurred at a sludge age of 12 to 15 days. Nelson et al. (1981) state that this is due to increased amounts of

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extracellular polymers. Rossin et al. (1982) speculate that increased MLSS is not the only factor. Sterritt et al. (1981) and Stoveland and Lester (1980) note that effluent COD decreases as sludge age increases. Maximum metals removal coincided with minimum effluent COD at a sludge age of 12 days. Minimum metal removal was at a sludge age of six days which coincided with maximum effluent COD. These results suggest that soluble organic compound compete with the sludge for the adsorption of metals. Failure of the biomass to degrade these compounds resulting in poor effluent quality may result in decreased metal removal efficiency (Sterritt et al., 1981).

Values for average removal of individual metals indicate that some metals are typically removed more efficiently than others. Different metals are removed to various degrees by the different processes in primary and secondary treatment.

Literature values indicate that nickel is removed least efficiently of all the metals, usually less than 40%. Stoveland and Lester (1980) attribute this to a high affinity for soluble ligands. Cantwell et al. (1982) found no detectable free nickel in raw sewage; all was complexed. Rossin et al. (1982) state that nickel removal may only be by sedimentation of precipitated nickel. Chen (1974) found that nickel forms very little precipitate and that most precipitated nickel exists as particles less than eight microns, whereas most cadmium, chromium and copper are associated with larger particles that settle more readily.

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Gould and Genetelli (1984) state that adsorption of nickel by activated sludge may be site specific.

Some metals are removed primarily through precipitation rather than adsorption. Sterritt et al. (1981) concluded that lead and trivalent chromium are removed by precipitation while other metals are removed by adsorption. Rossin et al. (1983) found that removal of lead is related to suspended solids removal, indicating that lead is primarily in an insoluble form in wastewater. In the activated sludge process, as dissolved oxygen decreases, hexavalent chromium is reduced to the trivalent form which then precipitates (Brown et al., 1973, Stoveland and Lester, 1980).

Addition of chelating agents reduces uptake of metals by sludge (Cheng et al., 1975). These may be organic ligands, nitriloacetic acid (NTA), which is used in detergents, ethylenediaminetetraacetic acid (EDTA), which is used in industry, or others (Brown and Lester, 1979). Perry et al. (1984) found that NTA was 90% degraded after nine to thirteen days in the activated sludge process, but that metal interaction with NTA interferes with biodegradation. Cheng et al. (1975) found that the order of strength of competition for metal ions is: sludge<glycine<oxalate<NTA<EDTA.

Adsorption of various metals by activated sludge can vary depending on the concentrations of the other metals present. According to Lester (1983), activated sludge is a dynamic process;

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the influent metal concentrations are continually changing hence equilibria between the phases of the metals are constantly shifting. Gould and Genetelli (1984) found that metals could be "salted out" of sludge by addition of other metals except nickel. They concluded that the order of strength of competition was $Cu>Cd\geq Zn>Ni$. Sterritt and Lester (1981b) found the order of affinity of metals for sludge to be $Cr>Cd>Ag>Pb>Zn>Cu>Ni,Co,Mn,Mo$. Cheng et al. (1975) obtained similar results but also found that the order varies with pH. Sterritt et al. (1981) concluded that while some metals may compete for adsorption sites, competition for binding sites is generally negligible.

2.1.2.c DIGESTION

During the digestion process some of the metals in sludge will solubilize (Bloomfield and Pruden, 1975). Metals in digester supernatants can be 10 to 300 times the influent concentration (Brown et al., 1973). If the supernatant is recycled through the treatment plant it can be a significant source of metals in the sludge.

Any sulfate that enters the digester will be reduced to sulfide. Excess sulfide will precipitate the soluble metals. Typically less than one percent of the sulfate in the wastewater ends up in the digester. This is not enough to precipitate all the soluble metals present in the supernatant (Masselli et al., 1967).

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During digestion the mass of the sludge is reduced as organics are degraded in the stabilization process. Digested sludges are typically higher in metals than raw or undigested sludges from which they derive because metals are concentrated during digestion (Parr et al., 1978).

2.1.2.d COMPOSTING

Composting is the aerobic thermophilic decomposition of the organic constituents in sludge producing a relatively stable, inoffensive humus-like material (Ehreth and Walker, 1977). During the composting process temperatures between 55 and 65 degrees Celsius are attained, destroying pathogens and driving the evaporation of water. Volatile organics are reduced to carbon dioxide and water as the sludge is stabilized (EPA, 1979b).

In the composting process, sludge is mixed with organic amendments (such as wood chips). These amendments act as a bulking agent, increasing the porosity of the mix and reducing the moisture content. The amendments also can be added to supply a source of limiting nutrients, such as carbon. The mixture is aerated by repeatedly turning the pile or by forcing air through the pile. In some processes the bulking agent is separated from the compost after composting and recycled for subsequent use.

There is very little information in the literature concerning the fate of metals during composting. The concentrations of heavy

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metals in the final compost will depend on several factors. These are:

1. the concentrations of heavy metals in the parent sludge,

2. the loss of metals through leaching,

3. increase in the organic content of the compost due to addition of organic amendments,

4. decrease in the organic content of the compost due to degradation of organics,

5. addition of metals in the composting amendments and

6. physical/chemical interactions between the compost and the bulking agent.

Metals are essentially conserved during composting; less than one percent are lost through leaching (Obrist, 1987). The concentration of metals in compost will be determined primarily by the percent change in organic matter during composting and any metals that may be added to the sludge in the composting amendments (Higgins, 1984, Higgins et al., 1980, Parr et al., 1978).

The heavy metals concentrations of compost will vary with the composting practice, the extent of digestion and the amount of amendments blended with the sludge (Black and Veatch, 1987). During the composting process volatile organics are lost from the sludge as the organic matter is degraded. Approximately 40% of the initial total solids will be degraded due to organic matter destruction. This will result in a corresponding increase in the

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final metals concentration (Higgins et al., 1980). Parent sludges that have been previously digested will have higher metal concentrations than undigested sludges. Degradation of organics during the composting process will be less than for undigested sludges (Parr et al., 1978). Organic amendments such as woodchips, peanut hulls or leaves can provide a dilution effect lowering the metals concentration below that of the parent sludge (Alpert et al., 1981, Mosher and Anderson, 1977, Parr et al., 1978).

The composting amendment can directly influence the metals content of the final compost. If the amendment is not separated from the compost at the end of the process, then any metals in the amendment will increase the mass of metals in the compost. The use of recycled compost that contains metals as a bulking agent is an example (Higgins, 1984).

Physical and chemical interactions between amendments and sludge can affect the metals content of the compost. Shredded tires are used as a bulking agent. They contain metals, primarily iron and zinc, which become incorporated into the compost raising the metals levels (Higgins, 1984).

Sorption of sludge metals onto the amendments has not been specifically studied. In a related study, however, Benson (1980) examined the sorption of metals in landfill leachate onto sawdust. He determined that the sawdust had a fixing capacity of 113

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meq/kg.  Part of this fixing capacity was due to cation exchange reactions and part was due to complexation reactions.

Table 4 gives metal concentrations for several composts and their parent sludges.

## 2.2  SOURCES, FATE AND IMPACTS OF METALS

### Non-industrial Sources

Sources of metals in sludge include background levels in the domestic water supply, domestic additions, industrial discharges, surface runoff and sewer infiltrations (Wood and Tchobanoglous, 1975).

Klein et al. (1974) studied the sources of cadmium, copper, chromium, nickel and zinc in New York City wastewater.  They concluded:

1.  Except for nickel at 62%, the electroplating industry does not contribute the major portion of the metals in the wastewater.

2.  Other industries contribute less than 9% of metals.

3.  Residential contribution of metals varies from 25-49%. Residential discharge of copper, cadmium, and zinc is considerably greater than industrial discharge.

4.  Water distribution systems contribute 67% more copper than electroplaters and half as much zinc.

5.  Storm water runoff contributes more copper and zinc than electroplaters and about 10% of the other metals.

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TABLE 4   METAL CONCENTRATION OF COMPOST (AND PARENT SLUDGE)
         (Parts Per Million)

| Ref. | Amends. | Cd | Cr | Cu | Fe | Ni | Pb | Zn |
|------|---------|-----|------|------|--------|------|------|--------|
| (a) | wood<br>chips | 8<br>(10) | --<br>-- | 300<br>(420) | --<br>-- | 55<br>(85) | 290<br>(425) | 770<br>(980) |
| (a) | wood<br>chips | 9<br>(19) | --<br>-- | 250<br>(725) | --<br>-- | --<br>-- | 320<br>(573) | 1000<br>(1760) |
| (b) | shredded<br>tires +<br>recycled<br>compost | 39<br>(35) | --<br>-- | 633<br>(520) | 20177<br>(8096) | 85<br>(86) | 513<br>(439) | 2200<br>(1043) |
| (b) | shredded<br>tires +<br>wood<br>shavings | 36<br>(35) | --<br>-- | 591<br>(520) | 18284<br>(8096) | 77<br>(86) | 489<br>(439) | 1950<br>(1043) |
| (c) | wood<br>chips | 1.5<br>(4) | 30<br>(90) | 140<br>(600) | --<br>-- | 7<br>(50) | 43<br>(80) | 360<br>(600) |
| (c) | brush<br>chips | 0.5<br>(2.4) | 96<br>(870) | 60<br>(340) | --<br>-- | 17<br>(13) | 74<br>(230) | 80<br>(390) |
| (d) | bark | 0.7<br>(4.8) | 17<br>(28.6) | 83.9<br>(278) | 4173<br>(7550) | 25.2<br>(22.6) | 118<br>(408) | 154<br>(453) |

(a) Parr, et al., 1978
(b) Higgins, 1984
(c) Donovan, et al., 1985
(d) Mosher and Anderson, 1977

Yost and Wukasch (1983) studied the metals contributions by industrial and residential discharges in Kokomo, Indiana. Residential inputs of these metals did not exceed 7% of the industrial inputs. Davis and Jacknow (1975) investigated metals in urban wastewater. They found that residential loadings supplied 19 to 63% of the metals studied. Table 5 gives values for the percent contribution of metals by residential sources to municipal wastewater. Table 6 gives measured values for metals in urban runoff.

Gurnham et al. (1979) conducted a detailed analysis of the sources of metals in domestic wastewater. Metals concentrations and loadings for sources such as household products, foodstuffs, runoff, tapwater and soils were studied. Table 7 gives per capita mass loading of metals by various residential sources.

Data from some treatment plants suggest that the water supply system is the major source of metals in wastewater (Brown, 1985, Davis and Jacknow, 1975, Fair et al., 1968, Sommers et al., 1976). Corrosion of distribution piping and home plumbing along with the use of corrosion inhibitors are sources of cadmium, copper, zinc, and lead. This occurs with low alkalinity, low pH surface waters or low pH, high dissolved $CO_2$ groundwaters (Brown, 1985).

Brown (1985) estimated the minimum concentrations of metals in tap water that would result in metal levels in sludge in excess of land application guidelines. He compared these values with

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TABLE 5   PERCENTAGE OF METAL LOADING FROM RESIDENTIAL SOURCES

| | Reference | |
| | Davis and | Klein et al. |
| Metal | Jacknow (1975) | (1974) |
| --- | --- | --- |
| Cd | 63 | 49 |
| Cr | 23 | 28 |
| Cu | 96 | 47 |
| Ni | 63 | 25 |
| Pb | 19 | - - |
| Zn | 32 | 42 |

TABLE 6   CONCENTRATIONS OF METALS IN URBAN RUNOFF (mg/l)

| | |
| --- | --- |
| Cd | 0.025 |
| Cr | 0.16 |
| Cu | 0.46 |
| Ni | 0.15 |
| Zn | 1.6 |

Source: Klein et al. (1974)

TABLE 7   HEAVY METAL MASS FLOW FROM RESIDENTIAL SOURCES
(micrograms per capita per day)

| Metal | Tap Water | Foods | Commodities | Total |
| --- | --- | --- | --- | --- |
| Cd | 518 | 482 | 81 | 842 |
| Cr | 845 | 364 | 662 | 1,871 |
| Cu | 7,580 | 2,909 | 510 | 10,996 |
| Pb | 2,612 | 331 | 272 | 3,215 |
| Hg | 110 | 27 | 7.5 | 144 |
| Ni | 4,590 | 699 | 23,449 | 28,738 |
| Zn | 12,204 | 11,953 | 738 | 24,895 |

Source: Gurnham et al. (1979)

data for drinking water in Boston and Seattle. The reported concentrations of copper in these waters were above the calculated value.

### 2.2.2   Hazards Posed by Metals

There is some variation in the literature concerning precisely which metals present the more serious hazards. Chaney (1974), states that the elements in sludge and effluent that are potential hazards to plants or the food chain are B, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn. Elinder and Kessler (1984) state that possibly toxic elements are Al, V, Co, Ni, Mo, Sn, and Sb, while elements causing major health problems are Hg, Pb, Cd, and As. Dean and Seuss (1985) concluded that with the exception of cadmium, heavy metals in sludge are not expected to affect human health through accumulation in food and fodder plants. EPA (1976) identified those elements posing relatively little hazard as Mn, Fe, Al, Cr, As, Se, Sb, Pb, and Hg. Elements posing a potentially serious hazard were Cd, Cu, Mo, Ni, and Zn. Brown and Lester (1979) identify metals of concern as Cr, Mn, Fe, Co, Cu, Zn, Mo, Ag, Hg, Cd, and Ni. Gleason et al. (1984) note that elements such as Cu, Zn, Mo, and Fe, present in sewage sludge added to agricultural soils at agronomic rates can help alleviate trace metal deficiencies in plants. An increase in plant trace metal content following sewage sludge application can also reduce the need for supplements of such elements as Se and Mo in animal diets.

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Zenz et al. (1975), commenting on proposed EPA regulations to
control land application of sludge, cited several studies to argue
that the regulations were too restrictive. They stated that:

1. The metals may be precipitated to sparingly soluble
   inorganic forms that are not available to plant growth.

2. The metals are absorbed by organic matter reducing their
   activity.

3. Metals are held back by the soil-root barrier. The
   rejection of metals varies not only with species but
   even with strains.

4. Metals taken up by roots accumulate preferentially in
   the stems and leaves and are not translocated to the
   fruits or grains. Total metal uptake by young plants is
   a poor indication of the hazard to human food.

5. Metal toxicity usually inhibits growth before
   concentrations toxic to humans have been reached in the
   parts used for food.

6. Not all metals present in foods are assimilated into the
   body burden. Cadmium, for example, is rapidly excreted
   in the feces; only three to eight percent is slowly
   excreted and contributes to the body burden.

2.2.3  Individual Metals


2.2.3.a  CADMIUM


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It is widely agreed upon that cadmium is the element that poses the most serious health hazard in the food chain. Cadmium is readily taken up and accumulated by plants without phytotoxic effects (Chaney, 1974, Dean and Seuss, 1985). Chronic health effects may result through diet and cigarette smoking, which are the main routes of uptake for most people (EPA, 1979a).

Cadmium is not an essential element. It resembles zinc in its chemical and physical properties. The average dietary intake in non-polluted areas is 10-25 micrograms per day. Simultaneous intake of calcium, zinc or iron at low levels can increase cadmium absorption. Cadmium toxicity is affected by the quantity and quality of protein in the diet. Only about 5-6% of the cadmium in food or beverage is taken up by the body, but 50-75% of this amount is deposited in the liver and kidneys (Waldron, 1980). Long term exposure can result in kidney or liver damage (EPA, 1979a).

Cadmium is taken up by plants and translocated to other parts of the plant. Leafy vegetables and root crops accumulate cadmium in their tissues. Tobacco also accumulates cadmium, increasing the exposure of cadmium for smokers (EPA, 1979a).

Cadmium is found in low levels in rocks, soil and water (Waldron, 1980). The chemistry of cadmium in the soil is not well understood. It is apparently influenced by organic matter, clay content and type, hydrous oxide content, pH and redox potential (EPA, 1976). At pH levels between 6 and 9, metal hydroxide and

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carbonate precipitates form, limiting cadmium availability (Dean and Seuss, 1985).

Industrial uses of cadmium include low melting alloys and solders, electroplating, batteries, and photoelectric cells. Cadmium is found as an impurity in zinc and superphosphate fertilizers. It is used in pigments, plastics, detergents, heating and lubricating oils and coal. Cadmium can be found in industrial, commercial and residential wastewaters as well as storm runoff (Dean et al., 1972, Klein et al., 1974, Waldron, 1980).

## 2.2.3.b  COPPER

EPA (1976), classified copper as an element posing a potentially serious hazard. Chaney (1974), considers copper a significant food chain hazard. He also states that copper will cause severe plant injury before it reaches levels toxic to animals, except sheep. Dean and Seuss (1985), state that plants are an effective barrier against copper toxicity in animals.

Copper is an essential element for all organisms. Copper is essential to plants but it can be phytotoxic at higher concentrations. Under toxic conditions most copper remains in the roots-very little is transported to aerial portions. Sheep are the most susceptible to copper toxicity, followed by cattle, swine and poultry. Swine, sheep and cattle can accumulate copper in the liver. Molybdenum deficiency is antagonistic to copper toxicity.

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Controlling molybdenum intake can prevent copper toxicity. High levels of copper in the diet are beneficial to swine and chickens. Debate concerning the addition of high levels of copper to animal diets has focused primarily on copper toxicity to plants grown on land treated with the animal wastes (EPA, 1976).

Copper is found in all soils, usually in the range of 10-80 ppm (Leeper, 1978). In soils it is associated with hydrous oxides of Mn and Fe, and soluble and insoluble complexes with organic matter (EPA, 1976). Copper toxicity usually occurs on acid soils. Control of pH can limit copper availability to plants (Dean and Seuss, 1985).

Sources of copper include pulp and paper, petroleum refining, and metal works industries. Other sources are soft drink production, laundries, food processing, algal control chemicals, residential wastewater and urban and rural runoff (Dean et al., 1972, Klein et al. 1974). Water supply systems can be a major source of copper. Water supplies can be high in copper due to erosion and corrosion of residential plumbing by low alkalinity waters (Brown, 1985).


2.2.3.c  CHROMIUM

Chromium exists naturally either in trivalent or hexavalent forms. Hexavalent chromium is toxic to plants, animals and humans. Trivalent chromium is an essential element for all organisms--required for glucose metabolism (Elinder and Kessler,

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1984). The main source of chromium in humans is food. Meat, whitefish, vegetables, unrefined sugar and vegetable oil are the largest sources to man (Waldron, 1980).

In the soil chromium(VI) is rapidly reduced to soluble chromium(III), which is converted to insoluble chromium(III). In the wastewater treatment process chromium(VI) is reduced to chromium(III) therefore sludge usually does not contain hexavalent chromium. Decomposition of sludge in soil is slow enough that there is no buildup of soluble chromium (EPA, 1976).

Dean and Seuss (1985), state that sludge borne chromium has no effect on plants or animals. EPA (1976), classified chromium as an element posing relatively little hazard. Sources of chromium include pulp and paper, chemical, and fertilizer manufacturing, petroleum refining, metal works, metal plating, glass, cement, asbestos and textile manufacturing, and steam generation (Dean et al., 1972). Chromium is also used in leather tanning, dyeing, photography and lithography (Waldron, 1980). Sources of chromium in commercial wastewater include bakeries, food processing, laundries and car washes.

2.2.3.d LEAD

Lead is a non-essential element that is capable of causing major health problems. The major sources of exposure in humans are food, wine, water, dust and paint (Elinder and Kessler, 1984).

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Lead in sludge poses relatively little hazard. Lead forms insoluble compounds or is sorbed in soils becoming unavailable to plants. Soluble lead in the soil reacts with clay, phosphate, carbonate, hydroxide, sesquioxide and organic matter to greatly reduce solubility. Lead is taken up by plants in ionic form. Uptake decreases with pH, cation exchange capacity and available phosphorus (EPA, 1976). Any lead that is taken up by plants tends to remain in the roots. The shoots obtain very little soil lead (Dean and Seuss, 1985). The main source of lead in plants is atmospheric deposition (Waldron, 1980).

Other routes of lead transfer provide the only health risks to humans and animal. Direct ingestion of sludge or sludge amended soil by animals or humans is the most serious health risk. This may be due to direct soil ingestion by animals while grazing, ingestion by animals or humans of plants on which sludge or soil deposition has occurred, or pica soil ingestion by humans. About 90% of the lead deposited in the body is in the skeleton, so intake of lead through ingestion of animal products is not a major health risk to humans (Dean and Seuss, 1985).

Sources of lead include pulp and paper, chemical and fertilizer manufacturing, petroleum refining and metal works and battery manufacturing. Other sources include paints, dyes, solders, automobile and smelter emissions, corrosion of plumbing, food, soil and dust (Dean et al., 1972, Dean and Seuss, 1985, Waldron, 1980).

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## 2.2.3.e NICKEL

Nickel is an essential element in animals that is found in nearly all soils, plants and waters. Soils typically contain 10-100 ppm nickel. In the soil, nickel is adsorbed onto hydrous oxides of iron or manganese or is strongly chelated by organic matter (EPA, 1976).

The only form of nickel known to cause systemic effects in humans is nickel carbonyl. Insoluble forms of nickel have been linked to respiratory cancer (Elinder and Kessler, 1985). Nickel in sludge or sludge fertilized crops fed to animals has not led to bioaccumulation. Nickel ingested by humans is relatively nontoxic except to persons who are sensitive to nickel (Dean and Seuss, 1985).

Nickel is not known to be essential to plants. It is toxic to plants at levels greater than 50 ppm. Chaney (1974) states that nickel will be phytotoxic before reaching levels hazardous in the food chain. Toxicity usually occurs on acid soils. Controlling pH will reduce nickel toxicity in plants (EPA, 1976).

Nickel is found in fossil fuels, batteries, alloys, inks and varnishes. The most significant route of exposure in humans is by dermal contact (wearing of jewelry). Concentrations in food vary up to approximately 6 ppm (Waldron, 1980). Sources of nickel in wastewater include pulp and paper and fertilizer manufacturing, petroleum refining, metal works, bakery wastes and runoff (Dean et al., 1972, Klein et al., 1974).

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2.2.3.f  ZINC

Zinc is essential for the functioning of various enzymes in all organisms. Zinc is commonly deficient in crops and is typically added with fertilizers. Normal plant levels range from 10 to 100 ppm. Higher levels in plants can be phytotoxic and can be a food chain hazard (Chaney, 1974, Elinder and Kessler, 1984). Toxicity in plants occurs at tissue concentrations of several hundred ppm. A wide margin of safety exists between normal dietary intake and toxic levels in birds and mammals (EPA, 1976).

In the soil, zinc is sorbed onto clay and hydrous iron oxides and chelated by organic matter. In general, if the pH of the sludge-treated soil is maintained at recommended levels, zinc should not be a serious hazard to plants or the food supply unless the sludge contains exceptionally high levels of zinc (EPA, 1976).

Sources of zinc include pulp and paper, chemical and fertilizer manufacturing, petroleum refining, metal works and steam generation (19). Other sources are fat rendering, food processing, soft drink manufacturing, dyeing and laundries (Klein et al., 1974).


2.2.3.g  IRON AND ALUMINUM

Iron and aluminum are common elements in the soil. Most soils contain large amounts of iron and aluminum so that addition of sludges high in these elements will not significantly alter the

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soil composition.  Typically, iron and aluminum are not limiting factors in sludge application (EPA, 1976).

Iron and aluminum are soluble in the soil only at low pH or under reducing conditions.  Aluminum toxicity in plants is common below pH 5.0.  At pH above 5.5 iron and aluminum form sparingly soluble oxides and hydroxides.  Iron is mobile in the soil solution in minute amounts chelated with organic anions. With good soil management practices, most iron and aluminum in the soil solution will rapidly precipitate out as hydroxides (EPA, 1976, Leeper, 1978).

Sources of iron and aluminum include chemical and fertilizer manufacturing, petroleum refining and metal works (Dean et al., 1972).


2.2.3.h  MANGANESE

Manganese is an essential element.  Like iron and aluminum, manganese is available in the soil only at low pH or under reducing conditions.  At pH above 5.5 manganese forms insoluble tetravalent oxides or some stable organic complexes.  Under these conditions manganese can be toxic to plants.  Manganese may accumulate in plants if large amounts are present in the soil. High levels of soluble iron in the soil may induce manganese deficiency in plants.  Typically, manganese is not a limiting factor in sludge application (EPA, 1976, Leeper, 1978).

2.2.3.i  MOLYBDENUM

Molybdenum is an essential element in plants and animals.  It is a cofactor in seven enzymes.  In plants it is essential for nitrogen fixation and nitrate reduction (Le Gendre and Runnels, 1975).  Molybdenum does not appear to be phytotoxic at high concentrations in plants (EPA, 1976).

Tolerance of animals to molybdenum varies with species and age.  Excessive molybdenum in the diet of animals causes copper and phosphorus deficiencies.  The condition is correctable with copper and phosphorus supplements.  It is doubtful that molybdenum in sludge would present a serious health hazard to grazing animals except where forages from sites treated with sludge high in molybdenum form the major part of the animal diet (EPA, 1976).

In the soil molybdenum exists primarily in an anionic form.  The soil has no general mechanisms for retaining  molybdenum.  It can pass through the soil and enter the groundwater.  It is precipitated at high pH by calcium, and at low pH by iron and aluminum (Leeper, 1978).  Molybdenum has a great affinity for iron oxide particles.  Maximum sorption of molybdenum is at pH 4.2.  Availability increases with pH.  Keeping the pH near neutral does not limit availability.  Phosphorus can replace molybdenum on oxide particles (EPA, 1976).


2.2.3.j  SELENIUM

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Selenium is essential for some animals. A narrow range

exists between deficiency and toxicity in animals--0.5 to 4 ppm.

Selenium can counteract mercury toxicity in some animals. There

is little evidence that selenium is essential to plants, but it is

taken up by plants (EPA, 1976).

In the soil selenium is least soluble at low pH. Under

neutral to alkaline conditions it exists as the selenate anion

which is quite soluble and does not sorb onto clay particles.

Cappon (1984) found that sludge and compost were less effective in

maintaining selenium buildup in the soil. Selenium volatilization

from the soil may be enhanced by sludge or compost. More

information is needed to evaluate the potential hazard from

selenium in sludge (EPA, 1976).


2.2.3.k  BORON

Boron is essential for plant growth. There is a very narrow

margin between soil levels of boron that produce deficiency

symptoms and that cause toxicity in plants. Deficiency symptoms

occur at 0.04 mg/l water soluble boron. Toxicity occurs at soil

solution concentrations above 1.0 mg/l (EPA, 1983).

In wastewater boron exists mainly in the form of the

undissociated boric acid molecule. Being uncharged, it passes

through the soil more readily than other elements. In humid and

semi-humid regions, rainfall is usually sufficient to leach

applied boron from the root zone (EPA, 1983).

2.2.4  Environmental Pathways

The EPA, in developing its regulations on sludge disposal,

created a list of chemicals selected for environmental profile

development.  These chemicals then underwent further risk

assessment to rate the hazards that they present in sludge

(Lomnitz et al., 1985).

The EPA also identified the pathways by which these chemicals

would influence the environment during sludge disposal.  The

metals and pathways identified for land application and

landfilling of sludge are listed in Table 8 (Lomnitz et al.,

1985).

2.3  REGULATIONS

Land application of sludge is regulated by the federal

government and by most state governments.  The EPA has limited

regulations on land application and defers to state regulations in

most matters.  Many states have incorporated EPA regulations and

guidelines into their regulations.

There are two types of regulations.  Some regulations control

the disposal process.  They specify how the land application

process is to be managed and/or set limitations based on

characterisitics of the disposal site.  The force of these

regulations is typically on the operator of the land application

site.  Other regulations control the sludge to be utilized in the

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TABLE 8   METALS AND ENVIRONMENTAL PATHWAYS STUDIED FOR
          DEVELOPMENT OF REGULATIONS


LAND APPLICATION OR DISTRIBUTION OF SLUDGE PRODUCTS

SOIL BIOTA TOXICITY:
 Copper

TOXICITY TO SOIL BIOTA PREDATORS:
 Cadmium, Zinc, Lead

PHYTOTOXICITY:
 Cadmium, Chromium, Copper, Nickel, Lead, Zinc, Selenium

ANIMAL TOXICITY FROM PLANT CONSUMPTION:
 Zinc, Molybdenum, Selenium, Copper, Cadmium, Iron

HUMAN TOXICITY FROM PLANT CONSUMPTION:
 Cadmium, Zinc, Nickel, Lead, Selenium, Arsenic, Iron, Mercury

HUMAN TOXICITY FROM ANIMAL PRODUCTS:
 Selenium, Zinc, Mercury, Cadmium

HUMAN TOXICITY FROM INCIDENTAL INGESTION:
 Arsenic, Lead, Mercury, Cadmium, Iron


LANDFILLING OF SLUDGE

HUMAN CONSUMPTION OF CONTAMINATED GROUNDWATER:
 Arsenic, Lead, Copper, Mercury, Nickel

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Source: Lomnitz et al. (1985)

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land application process. They limit the land application process according to the sludge characteristics. The force of these regulations is typically on the operator of the treatment facility or the distributor of the sludge product. In many states these regulations provide little or no regulatory control once the sludge has been distributed to the end user.

Currently, the only metal regulated by the EPA is cadmium. Cadmium loadings are subject to both annual and cumulative restrictions. The maximum annual loading is 0.5 kg Cd/ha. The maximum cumulative loading varies from 5 to 20 kg Cd/ha with the pH and cation exchange capacity (CEC) of the soil. These cumulative loading restrictions are given in Table 9.

EPA regulations also contain a second approach to cadmium control. Unlimited application of cadmium is allowed providing that four specific control measures are taken. First, the crop grown can only be used for animal feed. Second, the pH of the soil must be maintained at 6.5 or above as long as the food chain crops are grown. Third, a facility operating plan must describe how the animal feed will be distributed to prevent human ingestion. The plan must describe measures that will be taken to prevent cadmium from entering the human food chain due to alternative future land uses of the site. Fourth, future owners are provided notice (through provision in land record or property deed) that there are high levels of cadmium in the soil and food chain crops should not be grown (EPA, 1979a).

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TABLE 9  MAXIMUM CUMULATIVE METAL LOADINGS ON LAND

| Metal | Soil Cation Exchange Capacity (meq/100g) | | |
|---|---|---|---|
| | 0-5 | 5-15 | >15 |
| | Maximum Cumulative Loading (kg/ha) | | |
| Cd (1) | 5 | 10 | 20 |
| Cu (2) | 125 | 250 | 500 |
| Pb (2) | 500 | 1000 | 2000 |
| Ni (2) | 125 | 250 | 500 |
| Zn (2) | 250 | 500 | 1000 |

(1) EPA regulation
(2) EPA guideline

In addition to regulating cadmium, the EPA has also issued guidelines on the maximum cumulative loadings for lead, zinc, copper and nickel. The maximum loadings vary with the CEC of the soil. Table 9 lists these guidelines.

The impact of heavy metals in municipal sludge on land application programs will vary from state to state depending on each state's regulations. States differ in the extent of regulation, what aspects of the sludge disposal process are regulated as well as the actual standards that are set.

States' regulations vary in the number of standards and requirements that are explicit. For example, some states limit the cumulative metals loadings of the soil, others set maximum permissible sludge metals concentrations and some states use both standards. States' regulations can also vary in the number of land disposal options that are explicitly regulated. Some states regulations refer only to land application in general, while others have separate standards for such options as agricultural use, land reclamation, roadside use, composting and distribution.

Most states require that each sludge application site be approved by the regulating agency. A typical site application contains a physical description of the proposed site and explains how the land application program will be managed. In some states the site application documents the compliance of the design with the regulations. In other states where there are fewer explicit

requirements, the regulating agency considers each site
application on a case by case basis.

States' regulations can also differ with respect to other
aspects of land applications and heavy metals. Some states issue
regulations, some issue guidelines and some use both. The
required interval between required sludge analyses can vary from
state to state. The number of metals that are regulated also
varies from state to state.

Appendix A contains a summary of state regulations of land
application of sludge with respect to heavy metals for a number of
states in the Northeast. In addition, Metcalf and Eddy (1986) has
summarized the regulatory requirements for sludge compost
marketing and distribution in the U.S.


## 2.4 MANAGEMENT OPTIONS

Management options to deal with metals in sludge can be
divided into three catagories. Pretreatment prevents the entry of
the metals into the sewage treatment system. Additional
treatment of the wastewater or sludge removes the metals from the
sludge to be disposed of on the land. Land disposal options may
be selected based on the metals levels in the sludge.

### 2.4.1 Pretreatment

The EPA requires wastewater treatment plants to implement an
industrial pretreatment program to control entry of potentially

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harmful wastes into the system (Koch et al., 1982).  Zenz et al.
(1975) and Lue-Hing et al. (1978) examined the effect of the
pretreatment program of the Metropolitan Sanitary District of
Greater Chicago on the sludge cadmium content.  Zenz et al. found
that enforcing an industrial discharge standard of 2.0 mg/l
cadmium reduced sludge cadmium levels by as much as 72%.  In spite
of this, sludge cadmium levels were still well in excess of 25
ppm.  Lue-Hing et al. concluded that further reductions in the
discharge standard would cause only minimal improvement in
reducing cadmium loadings to the wastewater treatment plants.

Koch et al. (1982) estimated the impact of a pretreatment
program on the heavy metals content of sludge in two regional
wastewater treatment districts in New Jersey.  They concluded that
in one district a 70% reduction in cadmium levels of the sludge
was achievable.  However, this would only result in a 10% increase
in the amount of sludge that could be land applied because copper
would then become the limiting element.  They concluded that in
some areas pretreatment would provide only minor benefits to land
application programs.

Pretreatment programs can reduce both zinc and cadmium
levels.  The net effect can be a reduction, no effect or an
increase in Zn/Cd ratios.  This may not benefit land application
in states that regulate the Zn/Cd ratios of sludge (84).

Brown (1985) notes that when a water supply system is
responsible for significant metal loadings to a POTW, treatment

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practices can be instituted to control the problem. The major

obstacle is usually achieving interagency cooperation between the

governing bodies of the water supply and wastewater treatment

systems to deal with the problem.

## 2.4.2 Additional Treatment

Additional treatment to remove metals from wastewater or

sludge is not commonly practiced. A number of studies

investigating various treatment processes have been published.

Most are laboratory or pilot studies. Few have been implemented

on a large scale. Recovery of metals from sludge is not

economical at this time (Eckenfelder and Santhanam, 1981).

The most commonly investigated treatment process is acid

extraction of metals from sludge. The sludge is acidified to a pH

between 1.5 and 3.0 to solubilize the metals. Contact times

studied vary from 15 minutes (Scott and Horlings, 1975) to 24

hours (Wozniak and Huang, 1982). Metal removal is dependent upon

the pH attained, the metal being removed, percent solids of the

sludge and contact time (Wozniak and Huang, 1982).

Additional treatment is required to precipitate and remove

the metals from the acid extract. Also, the pH of the original

sludge must be returned to a level near neutral (Jenkins et al.,

1981). Acid extraction approximately doubles the cost of sludge

treatment and disposal (11).

Tyagi and Couillard (1987) investigated bacterial leaching of

metals from anaerobically digested sludge using Thiobacillus

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ferrooxidans and Thiobacillus thiooxidans. The bacterial leaching occured at aproximately pH 3.0. They found that these cultures solubilized 50% of the cadmium, 55% of the lead, 75% of the copper, and 95% of the zinc in the digested sludge.

Jenkins et al. (1981) compared acid treatment of sludge with extraction using EDTA. Results of the EDTA treatment varied for primary, waste activated and digested sludges. The EDTA treatment was more effective removing camium, copper and lead and less efficient for iron, chromium, nickel and zinc. The EDTA treatment is also much more expensive than acid treatment. They concluded that acid treatment of digested sludges was the better choice for metal removal.

Alibhai et al. (1985) examined EDTA treatment of sludge. They concluded that treatment with EDTA can:

1.  extract metals from sludge generating more sites for adsorption.

2.  extract extracellular polymers and perhaps reduce the metal binding capacity of the sludge.

3.  change the nature of the binding sites.

4.  render the sludge inactive. Inactivation does not affect binding capacity.

5.  reduce the alkalinity of the sludge.

At one time chlorine stabilization was commonly practiced as an alternative to anaerobic digestion. In this process chlorine gas is applied to the sludge in an enclosed tank. The chlorine

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reacts with the water to form HCl, lowering the pH and solubilizing the metals in the sludge (Obrist, 1987, Sterritt and Lester, 1982). The results obtained are similar to those for acid treatment. The release of metals is a function of the final pH, the type of sludge and the species of metal present. The filtrate from the chlorine oxidation process also has increased phosphorus and COD (Olver et al., 1975, Sukenik et al., 1977).

Chlorination of sludge can have adverse effects on the sludge and the environment after disposal. Chlorine oxidation forms a large number of chlorinated hydrocarbons in the sludge. Chlorinated sludge has been shown to reduce the growth of plants compared with unchlorinated sludge (Kamlet, 1979). Sukenik et al. (1977) concluded that the benefits of chlorine oxidation come from the acid effects while the chlorine effects could be deleterious.

Farooq and Aklaque (1982) investigated ozone oxidation of sludge to remove metals. They found that ozone released metals from sludge with only a slight decrease in pH. The alkalinity and COD of the sludge were also lowered by the treatment.

Huang (1982) conducted pilot plant studies using coprecipitation with lime in an upflow expanded sand bed. Calcium carbonate and the metal precipitates were plated onto the sand grains. The sand grain increased in size and eventually formed large dry chemical pebbles a few millimeters in diameter that were easy to handle in the disposal process.

Optimum removal was at pH 10.0-10.5 at pH 10.5 COD was
reduced 21%, suspended solids 38%, volatile suspended solids 43%
and total P 64%.

Fronk et al. (1985) investigated centrifugal treatment of
sludge. A continuous countercurrent bowl centrifuge was used to
separate sludge into two fractions. The heavier fraction
contained precipitated metals and heavy organics (including
pesticides). The efficiency of removal varied with the source of
the metal. Better removals were obtained for most metals using
digested sludge. They concluded that the process may be cost
effective for upgrading sludge for composting or land application.

Bloomfield and Pruden (1975) investigated the effects of
anaerobic and aerobic digestion on metal solubilization. They
found that aerobic digestion or anaerobic digestion followed by
aerobic digestion increased the amount of metals that were
leachable with water.

2.4.3  Land Disposal Options

Several land disposal options are available for sludge. Land
application is the application of sludge to land to enhance plant
growth. Landfilling is disposal of sludge in a sanitary landfill
with an impervious liner and cover. Dedicated land disposal is
burial of sludge in unconfined sites. Land reclamation is the
application of sludge to restore severely disturbed land such as
strip mining sites. Distribution is the distribution or sale of
dewatered or dried sludge or sludge products such as compost.

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While the impact of metals on each of these options will vary from state to state, based on individual state regulations, some general effects may be noted.

Land application is, typically, most heavily influenced by the metals content of the sludge. Some states' regulations distinguish between different land uses in land application. Land which is to be used for growing food chain crops is subject to more restrictions than other uses such as horticultural crops, forestry crops, recreational land or roadside development.

Dedicated land disposal and land application are less subject to impacts by the metals content of the sludge. Larger quantities of sludge and lower quality sludge typically may be used.

Landfilling, where allowed, is the least impacted disposal option. Sludge disposal in a landfill is usually unrestricted as long as the metals content does not classify it as a hazardous waste. This is typically not the case with municipal sludge. Landfills are often used to dispose of nonhazardous sludges that are too contaminated for other disposal options.

User oriented regulations promulgated to control land application of sludge are usually inadequate to control distribution of sludge products. Distribution of sludge products is usually controlled by product oriented regulations. Typically these regulations are as restrictive or more restrictive than those controlling land application.

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For any land disposal option, the regulations for the different metals will not have the same impact on the suitability of the sludge for disposal. Typically only one or two metals in the sludge will control the disposal options. The other metals usually are not present in sufficient quantities relative to the regulated maximum levels to effect disposal.

Mercury is usually one of the more tightly regulated metals found in sludge. Mercury, however, is typically found in sludges at such low levels that it is rarely a limiting element in sludge disposal schemes.

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CHAPTER III


EXPERIMENTAL METHODS AND MATERIALS


The experimental methods for this study were developed in

three steps:

1. Selection of an operating composting facility to study,

2. design of a sampling protocol, and

3. development of techniques for sample analysis.


## 3.1 FACILITY DESCRIPTION


The Hoosac Water Quality District treatment plant is located

in Williamstown, Massachusetts. It provides wastewater treatment

for Williamstown, North Adams and part of Clarksburg. The design

flow is 20440 $m^3$ per day (5.4 MGD). The average daily flow is

21200 $m^3$ per day (5.6 MGD).

The plant employs conventional activated sludge treatment.

Primary and secondary sludge are co-settled in the sedimentation

basins. The combined sludge is then conditioned with lime and

dewatered.

The sludge is dewatered on vacuum filters. The plant is

staffed five days per week for two shifts per day. The vacuum

filters typically operate continuously while the plant is staffed.


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The dewatered sludge is taken by truck from the vacuum filters to the composting area every thirty minutes. The composting area is on the grounds of the treatment plant. Wood chips are used as a bulking agent. The wood chips are added to the sludge in the truck, mixed and fed by a conveyor from the truck into the composting bins. The ratio of bulking agent to sludge is 2:1 by volume.

Figure 1 is a process diagram of the composting facility. Sludge is composted in aerated static piles in concrete bins. This is a batch process. Each bin is 21.4 meters long, 4.6 meters wide and 3.7 meters high. One end of each bin is open. The sludge and bulking agent mixture is fed from the truck into the bin from the top. In the floor of each bin are two channels covered with grates. These function as combination air plena and leachate drains. The leachate from the compost piles is recycled back to the plant.

It takes two to four days to fill a bin (approximately 460 cubic meters). There are eight bins. The bins are filled and emptied sequentially. As a new bin is needed, the oldest batch is removed. A front-end loader empties the bin via the open end. The residence time of a batch of compost is three to five weeks.

Mechanical blowers force air through the compost piles in the bins via the air plena. The blowers operate on a cyclic basis. A typical cycle is 15 minutes on and 15 minutes off. This procedure maintains sufficient aeration in the pile without cooling it to

TREATMENT
PLANT

STOCKPILED
COMPOST
(UNSCREENED)

LATE FALL TO
LATE SPRING

LATE SPRING
TO LATE FALL

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VACUUM
FILTERS

3 m$^3$ SLUDGE

EVERY
1/2 hr

BULKING
AGENT
ADDITION
(2:1 CHIPS
TO SLUDGE)

COMPOSTED
(in static piles)
3-5 weeks

LATE SPRING
TO LATE FALL

BULKING
AGENT
SEPARATION

CURING
PILE

BULKING
AGENT
STORAGE

BULKING
AGENT
RECYCLE
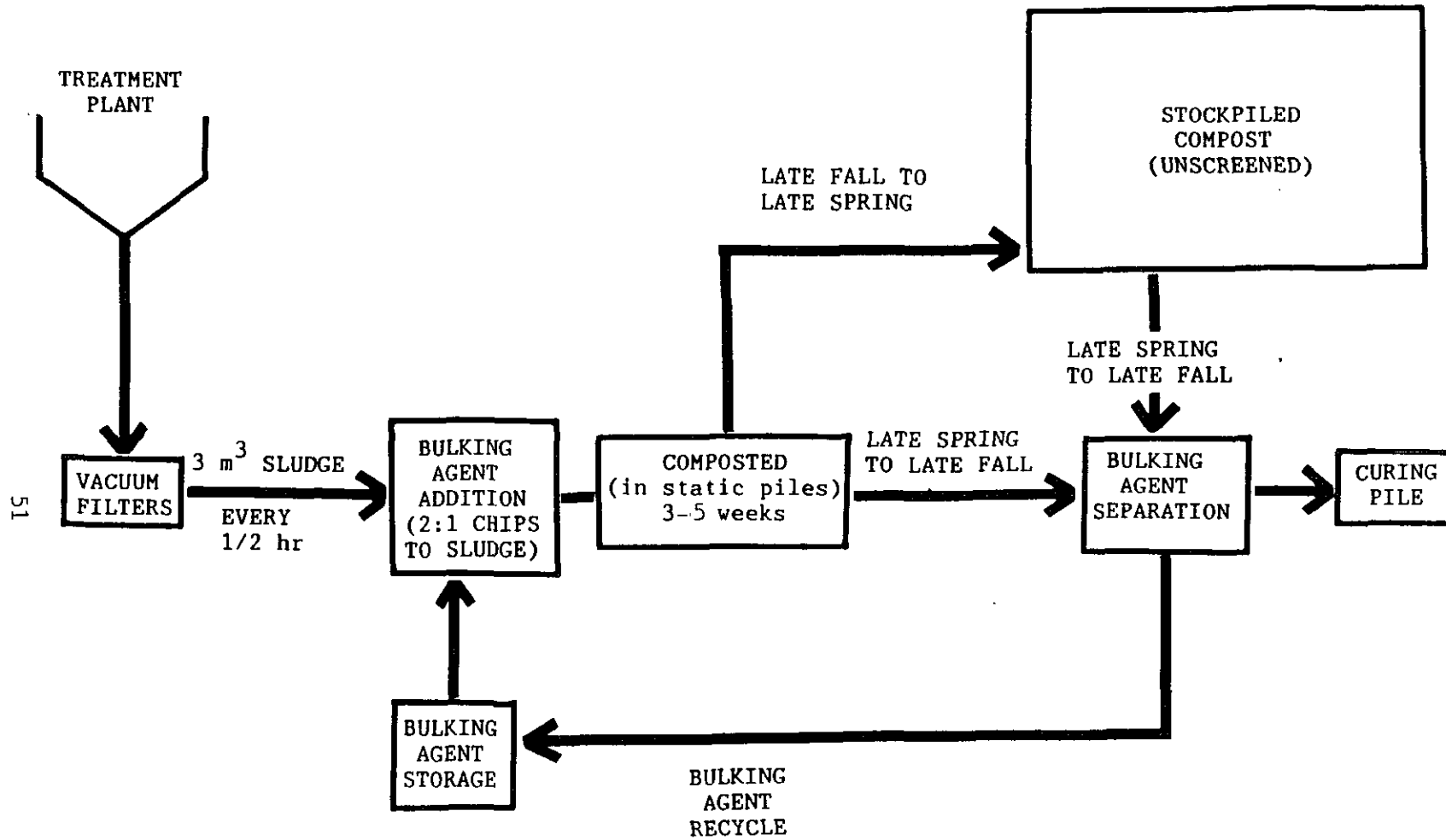
FIGURE 1  PROCESS DIAGRAM OF COMPOSTING FACILITY

below the thermophilic temperature range. Temperature probes inserted into the compost pile monitor the temperature in each batch.

In addition to the on-off cycling of the blowers, periodically the blowers are reversed. Each time the direction of air flow is reversed the air passes through different pathways in the pile. This increases the efficiency of the aeration process.

The method of handling the compost once it is removed from the bins differs depending on the time of year. During the warmer months the compost is screened to remove the bulking agent. A mechanical screener with a 0.5 inch mesh is used. The screened compost is then placed in a curing pile. It is kept in the curing pile for at least thirty days before it is disposed of. The wood chips are then recycled.

During the colder months evaporation from the compost piles is greatly reduced. Consequently, the compost produced from late fall to late spring is initially too wet to screen. During these months the compost plus bulking agent is stockpiled on site. Beginning in late spring the stockpiled material is screened and added to the curing pile.

The compost is classified under Massachusetts regulations as Type III material; subject to the strictest controls (see Appendix A). Because of the restrictions imposed, final disposal of the compost is in a landfill. The Type III classification is primarily due to high levels of cadmium from a single industrial

source (photochemical processing). This industry was required to install pretreatment by 31 March, 1988.

Because of the Type III classification, the plant does not sample its compost regularly. When a sample is collected, it is done by combining a number of randomly selected grab samples in a bucket. The contents are then mixed, and an aliquot of this material is removed for analysis.

## 3.2 SAMPLE COLLECTION

Three sampling procedures were designed for this study. Samples were collected from the sludge entering the composting process (sludge samples), the compost produced in each batch studied (batch compost samples) and the compost stored on site, either stockpiled or in the curing pile (stored compost samples).

Sampling programs for the sludge and the batch compost had similar objectives, but involved sampling from different types of populations. The objective of the sampling program for the sludge samples was to characterize the quality of each batch of sludge prior to composting. Sampling was from the continuous effluent solids stream of the treatment plant. This produced a time-based description of the sludge quality. The objective of the sampling program for the batch compost was to characterize the quality of the compost produced in each batch studied. Sampling from a batch of compost involved sampling from a population of independent concentrations at one point in time.

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Two methods of sampling were considered. A systematic sampling program--sampling at predetermined spatial or temporal intervals--is technically easier to design and conduct since non-random bias does not have to be prevented. The non-random bias must be quantified when analyzing the data. A random sampling program produces unbiased data, but it is more difficult to produce a sampling program that is completely random. If there is no systematic variation in the study parameters, however, then random sampling and systematic sampling are practically equivalent (Ellis and Lacey, 1980).

It was assumed that there were no mid- or long-term systematic variations in the parameters under study (e.g., diurnal or weekly variations) in the sludge. It was assumed that there were no systematic spatial variations in the quality of the batch compost. To test for short term variations in sludge quality (within three hours or less), a number of samples were collected and analyzed. The results revealed no such variations. Based on this information, it was decided to employ systematic sampling procedures.

The objective of the sampling procedure for the stored compost was to simulate the sampling method used by the treatment plant personnel when sampling for regulatory compliance. No attempt was made to identify or eliminate sources of bias in this procedure.

Two primary criteria for the sampling procedures for sludge and batch compost were established. The first was that they were not unduly complex. These samples were to be collected by treatment plant personnel so a procedure was desired that would not be excessively time consuming. Also, a simple procedure was more likely to be applicable to other sites, making it useful for future studies. The second criterion was that the procedures be statistically justifiable. Proposed sampling methods were reviewed by a consultant from the University Statisical Consulting Center who pronounced them to be suitable.

Figure 2 is a diagram of the sampling program. Sampling was conducted on every other bin filled. These batches were termed study bins. Sampling of sludge and batch compost was conducted by treatment plant personnel. Sampling of stored compost was conducted by project participants.

Sludge samples were taken at the vacuum filters. Samples were collected only when a study bin was being filled and when the vacuum filters were operating. Samples were collected at two hour intervals only during the first shift of plant operation. The maximum number of samples collected in one day was four. Samples were collected in 120 ml containers and stored under refrigeration.

Batch compost samples were collected when a study bin was emptied. Four samples of the unscreened compost and bulking agent mixture were collected when the bin was half emptied and four were

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VACUUM
FILTERS

```
UP TO FOUR 120 ml
SAMPLES COLLECTED
TWO HOURS APART
EACH DAY A STUDY
BIN IS FILLED
```

STATIC PILES
IN BINS

```
EIGHT 500 ml SAMPLES
COLLECTED (FOUR EACH
AT THE MIDDLE AND END
OF THE BIN) WHEN A
BIN IS EMPTIED
```

BULKING
AGENT
RECYCLE

STOCKPILED
COMPOST

```
SIX COMPOSITE SAMPLES
(THREE FROM CURING PILE
AND THREE FROM STOCKPILED
COMPOST) COLLECTED EVERY
TWO TO THREE WEEKS
```

CURING
PILE

FIGURE 2   DIAGRAM OF SAMPLING PROGRAM

collected when the bin was nearly emptied. Each sample was collected at a random point on the cut face of the compost pile in the bin. Samples were collected in 500 ml containers and stored under refrigeration.

Samples of stored compost were collected when visits were made to the site to retrieve sludge and batch compost samples. This was typically done once every two to three weeks.

Three samples were collected from the curing pile per visit. Each sample was a composite of smaller samples taken at random points on the pile. The smaller samples were taken a few centimeters below the surface of the pile. Sampling points were approximately evenly distributed around the circumference of the pile. These samples were collected in 500 ml containers and immediately transported for processing.

Three samples were collected from the stockpiled compost per visit. Like the samples from the curing pile, these samples were composites of smaller samples taken at points distributed over the surface of the pile. Because the stockpile was much larger than the curing pile, sampling was conducted in two steps. First, samples were collected from the pile in three 13 liter buckets. The contents of each bucket were then thoroughly mixed and one 500 ml aliquot was taken from each bucket.

During the course of the investigation, one sample of leachate from a compost bin was collected. Also, one sample of

filtrate from the vacuum filters and one sample of settled sludge prior to lime addition were collected.

## 3.3 SAMPLE PROCESSING AND ANALYSIS

Sample processing consisted of two steps: sample preparation and digestion. Sample preparation was necessary to transform the raw sample as brought from the site, into a dried sample. The dried sample was a uniform and representative aliquot of the raw sample that was suitable for digestion. The dried sample was digested to destroy the solids and solubilize the solid and bound metals. The digest was then analyzed for the metals under study. Figure 3 is a flow chart of the steps used for sample processing and analysis.

Sludge was prepared by first taking an aliquot (approximately 40 ml) of the raw sample. This material was dried at $103^{\circ}C$ overnight. The dried sludge was then ground with a mortar and pestle and redried at $103^{\circ}$ to produce a dried sample of sludge.

Samples of batch compost or stored compost contained significant portions of wood chips and wood chip fragments. The presence of a piece of wood in the sample to be digested would introduce a variable mass of inert material into the sample. This would result in an unquantifiable dilution of the heavy metals in the sample.

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RAW SLUDGE
SAMPLE

RAW COMPOST
SAMPLE

SAMPLES DRIED
$103^{o}C$ 24 to 48 hrs

SAMPLES DRIED
$103^{o}C$ OVERNIGHT

2 mm SIEVE
SEPARATION

DRIED SAMPLES
GROUND USING
MORTAR AND PESTLE

0.5 GRAM
DRIED SAMPLE
FOR DIGESTION

SAMPLES DIGESTED
IN NITRIC ACID

DIGESTS
FILTERED

ANALYSIS BY
ATOMIC ABSORBTION
SPECTROPHOTOMETRY
FOR Cd, Cr, Cu,
Ni, Pb, AND Zn
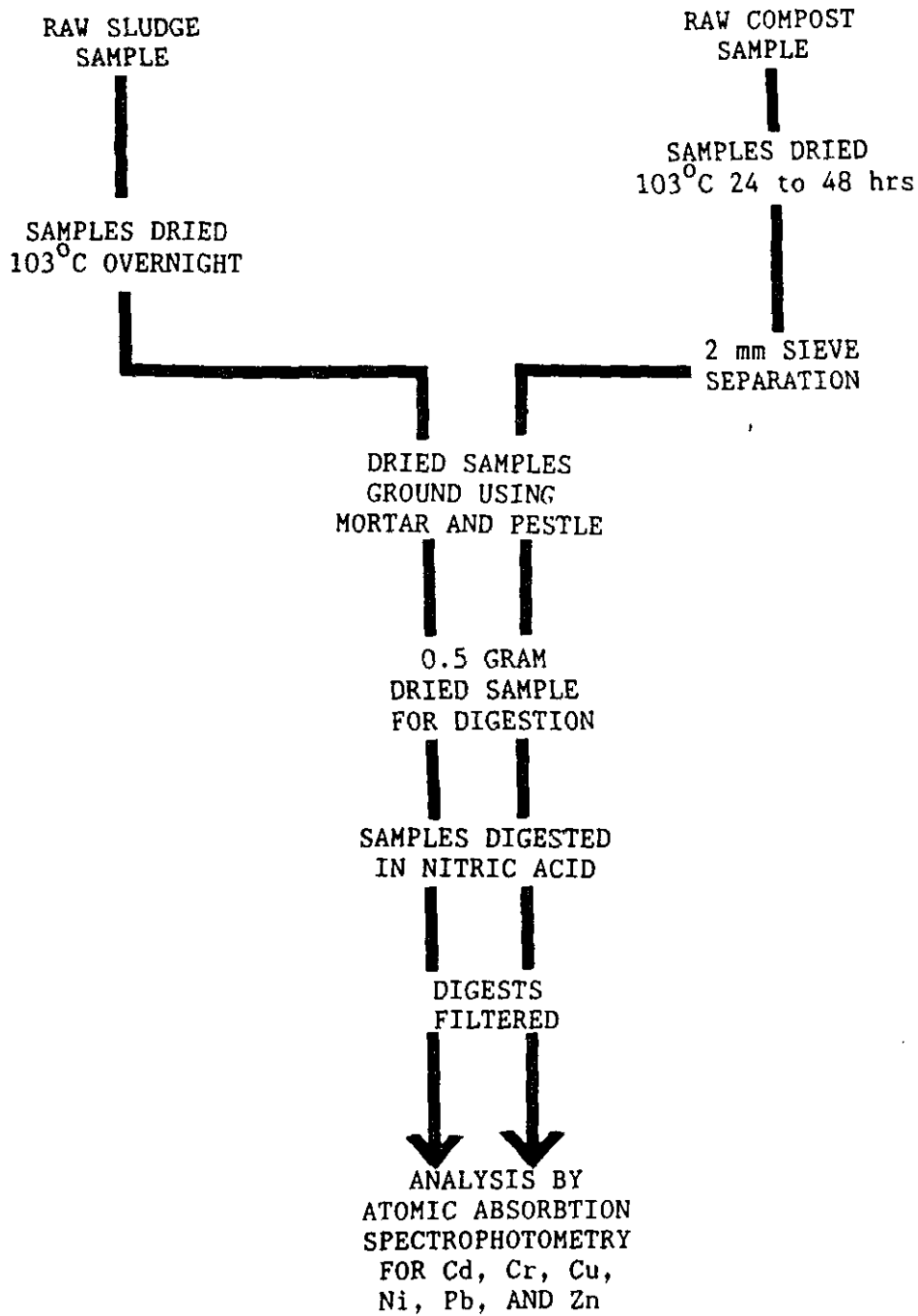
FIGURE 3    SAMPLE PROCESSING AND ANALYSIS FLOW DIAGRAM

To prevent this, a method of separation was needed that would remove the wood from the compost. No information was found in the literature describing such a method or defining the different fractions in this type of material.

The first step in devising a separation technique was to decide what portion of the wood should be removed. Removing all the wood would not be practical for two reasons. First, it would be difficult to identify and remove the smallest pieces of wood. These pieces are in the same size range as the particles of compost. Second, the composting process incorporates a certain amount of wood fragments into the final compost. The wood chips are physically and biologically degraded during composting and screening. The chips break into smaller pieces that cannot be recovered during the screening process (Haug 1980).

It was decided to sieve the compost to remove the wood. This technique is simple and easily applied to large numbers of samples. It also closely mimics the separation process employed at the treatment plant. Trial and error experimentation showed that a two millimeter sieve was ideal. It retained most of the larger wood chips yet passed almost all of the compost. Replicate metals analyses of processed samples yielded similar results.

A raw sample of batch compost or stored compost was dried at $103^{\circ}C$ for 24 to 48 hours. The sample was placed on a two millimeter sieve with ten 0.5 inch porcelain balls. The sieve was placed on a sieve shaker and shaken for 12 to 15 minutes. The

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porcelain balls dislodged the dried compost from the wood chips and broke up larger pieces of organic material allowing them to pass through the mesh.

The material remaining on the sieve--wood chips and larger bits of organic matter--was discarded. The material that passed the sieve still contained some larger fragments of wood. To remove these fragments the material was sieved two more times. Each time the sieve was shaken side-to-side gently by hand for about five seconds. The material that ultimately passed the sieve was considered to be just compost without any separable bulking agent.

The dried, sieved compost was then ground using a mortar and pestle. It was then redried at $103^{o}C$ to produce a dried sample of compost.

Dried samples were digested in nitric acid using a method described by Thompson and Wagstaff (1980). The method was developed for use in analyzing large numbers of samples. Because of the large number of samples collected in this study, replicate digestions were not performed.

Samples were digested in 25mm X 200mm screw top Pyrex culture tubes. These tubes were calibrated gravimetrically to 50 ml. A sample weighing 0.5 grams was placed in the tube, and three milliliters of deionized water and 6 ml of nitric acid (Baker Instra-analyzed, J.T. Baker Co.) were added. The tubes were then placed on an electric six-position Kehldal heating unit and the

solutions were heated to boiling. The solutions were gently refluxed for twenty minutes to digest the samples.

The digests were cooled to room temperature. They were then diluted to 50 ml in the tubes, capped and shaken gently. After settling for at least two hours, the digests were filtered through Whatman GF/C glass fiber filters (1.2 micron effective pore size). They were then ready to be analyzed.

Digested samples were analyzed for the metals under study (cadmium, chromium, copper, nickel, lead and zinc) using atomic absorption spectrophotometry. Analyses were performed using a Perkin-Elmer Model 3030B Atomic Absorption Spectrophotometer. The instrumental conditions for each metal analyzed are given in Appendix B, Table B1.

Mixed metal standards containing all six metals studied were used to standardize the spectrophotometer. The standards were prepared from commercially produced atomic absorption standards (Aldrich Chemical Company). The concentrations of each metal in the standards is given in Appendix B, Table B2. A blank solution was prepared using deionized water. The blank solution and all the standards were ten percent nitric acid by volume to match the matrix of the digests as closely as possible.

Digests were diluted 10:1 when analyzing for zinc. This was done so the sample concentrations would be within the linear range of the instrument. The diluted digests were also acidified to ten percent nitric acid by volume.

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A large sample digest was prepared and used for quality control monitoring. The QC sample was analyzed each time a set of samples was analyzed to monitor any variability from session to session in the spectrophotometer. The values of the QC sample readings are given in Appendix B, Table B3.

Representative sludge samples were analyzed for total solids content. Representative compost samples were analyzed for volatile solids content. Both these analyses were performed according to Standard Methods (APHA, AWWA, and WPCF, 1985).

CHAPTER IV


RESULTS AND DISCUSSION


4.1 BATCH COMPOSTING STUDIES


Sampling was conducted from January, 1988 through June, 1988.
Thirteen batches of sludge, designated A through M, were sampled.
Compost samples from batches D and E were lost. Complete data is
available for eleven batches. Table 10 lists the beginning and
ending dates of composting for each batch.

The results of the metals analyses of these samples are
presented in Appendix C, Table C1. The results of the metals
analyses of the sludge and batch compost for each batch were each
reduced to an average concentration of each metal in each batch.
These average concentrations are listed in Appendix C, Table C2.
These values are also presented in Figures 4 through 9 (cadmium,
chromium, copper, nickel, lead and zinc, respectively).

The cadmium concentrations in the sludge and batch compost
declined during the first half of the study period. This is
presumed to be due to the use of pretreatment by the industrial
discharger lowering the cadmium concentration in the raw
wastewater. Cadmium concentrations increased in the latter part
of the study period. The reason for this is not known.

The average cadmium concentration in the sludge varied from

TABLE 10  BATCH COMPOSTING SCHEDULE

| BATCH | DATE PILE CONSTRUCTED | DATE PILE REMOVED | DAYS COMPOSTED |
|-------|-----------------------|-------------------|----------------|
| A | 01/25 | 03/01 | 37 |
| B | 02/01 | 03/03 | 31 |
| C | 02/11 | 03/15 | 33 |
| F | 03/10 | 04/13 | 34 |
| G | 03/25 | 04/27 | 33 |
| H | 04/04 | 05/09 | 35 |
| I | 04/13 | 05/18 | 35 |
| J | 04/25 | 05/25 | 30 |
| K | 05/05 | 06/08 | 34 |
| L | 05/16 | 06/21 | 36 |
| M | 05/24 | 06/29 | 31 |
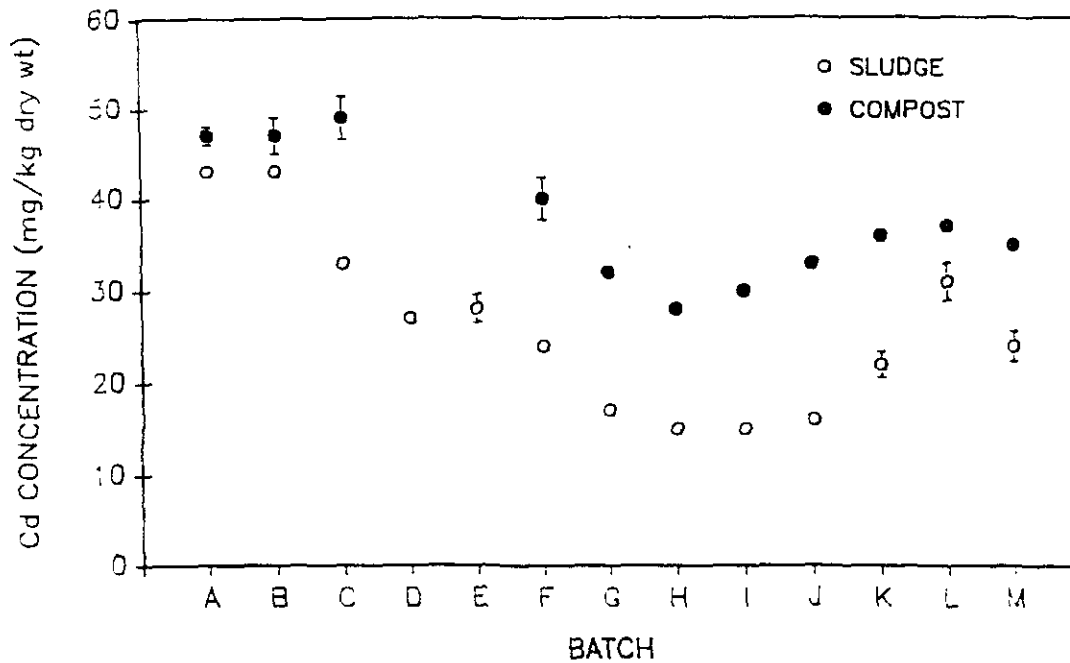
FIGURE 4  AVERAGE (± STD ERROR) CADMIUM CONCENTRATIONS
IN SLUDGE AND BATCH COMPOST SAMPLES
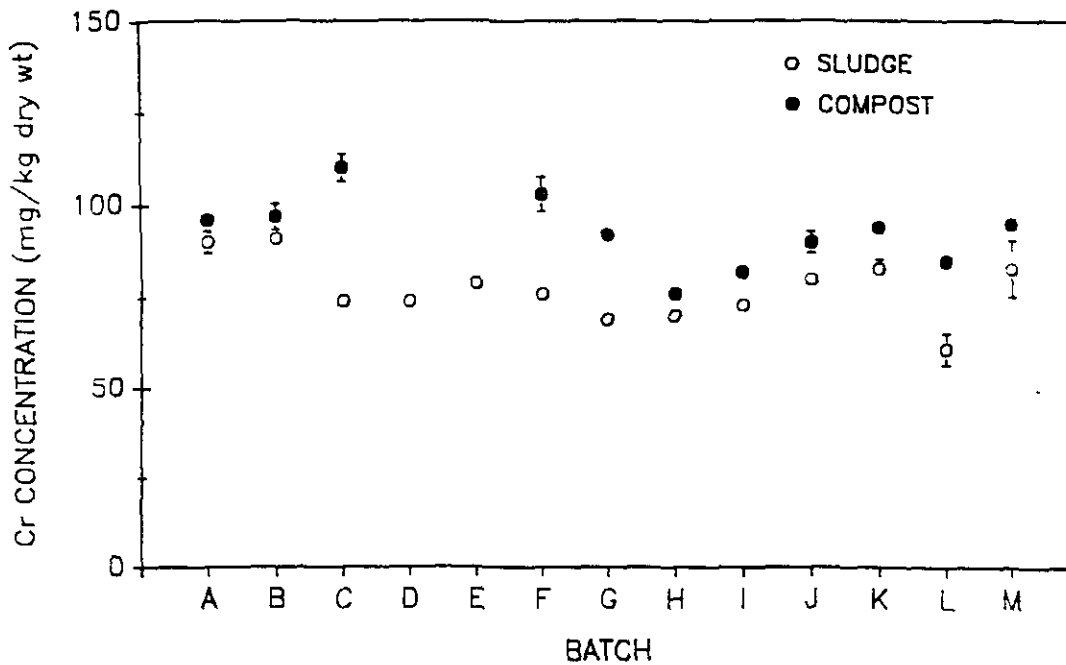


FIGURE 5  AVERAGE (± STD ERROR) CHROMIUM CONCENTRATIONS
IN SLUDGE AND BATCH COMPOST SAMPLES
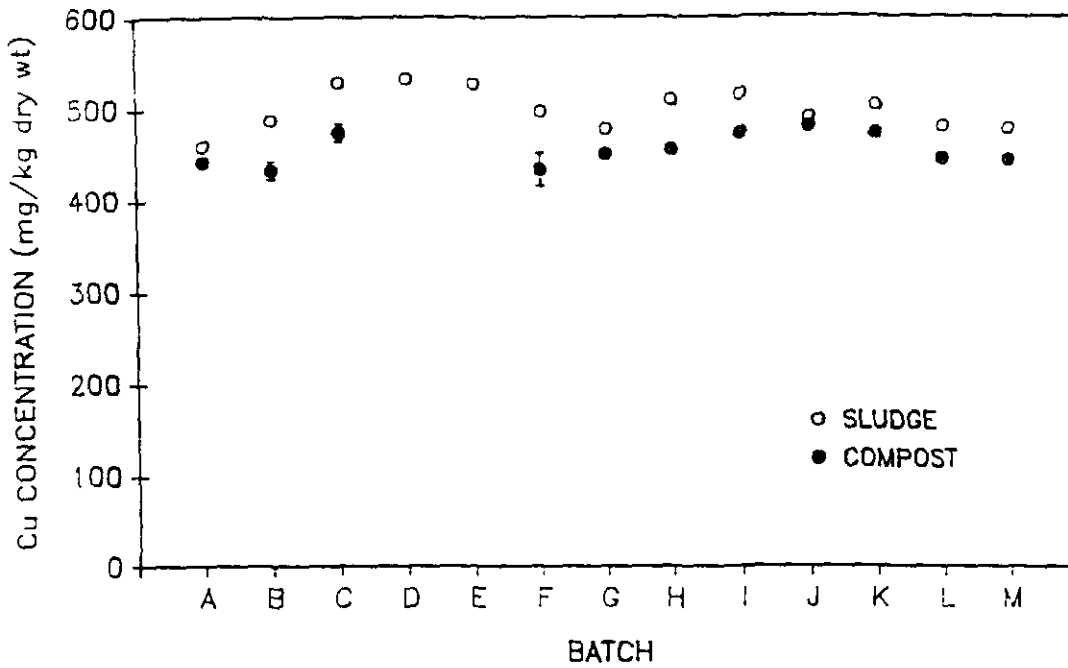
FIGURE 6  AVERAGE ($\pm$ STD ERROR) COPPER CONCENTRATIONS
IN SLUDGE AND BATCH COMPOST SAMPLES
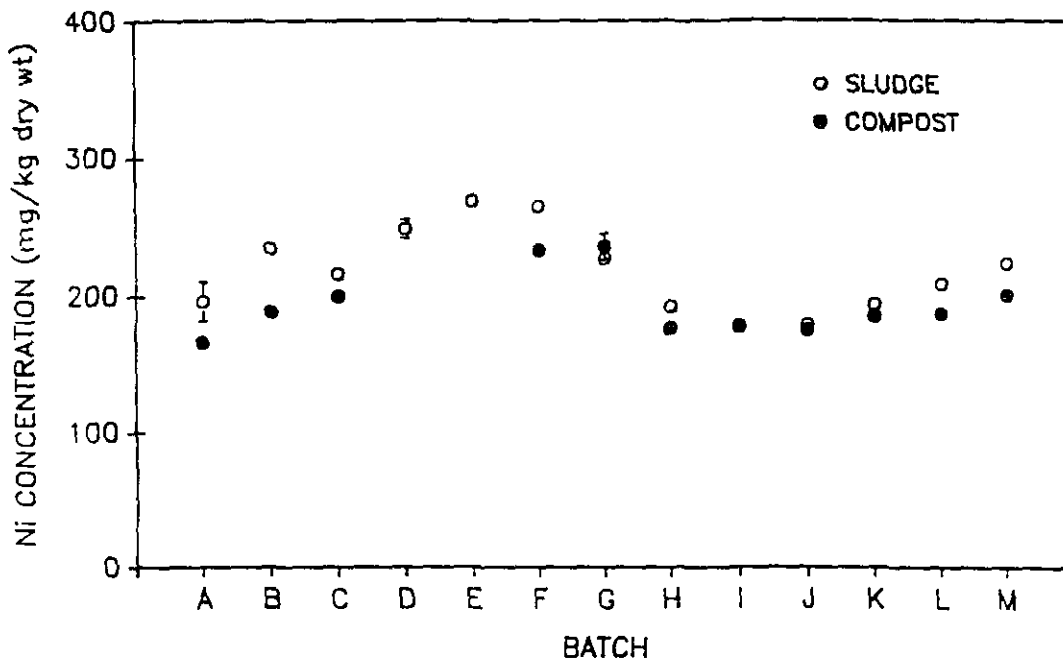


FIGURE 7  AVERAGE ($\pm$ STD ERROR) NICKEL CONCENTRATIONS
IN SLUDGE AND BATCH COMPOST SAMPLES

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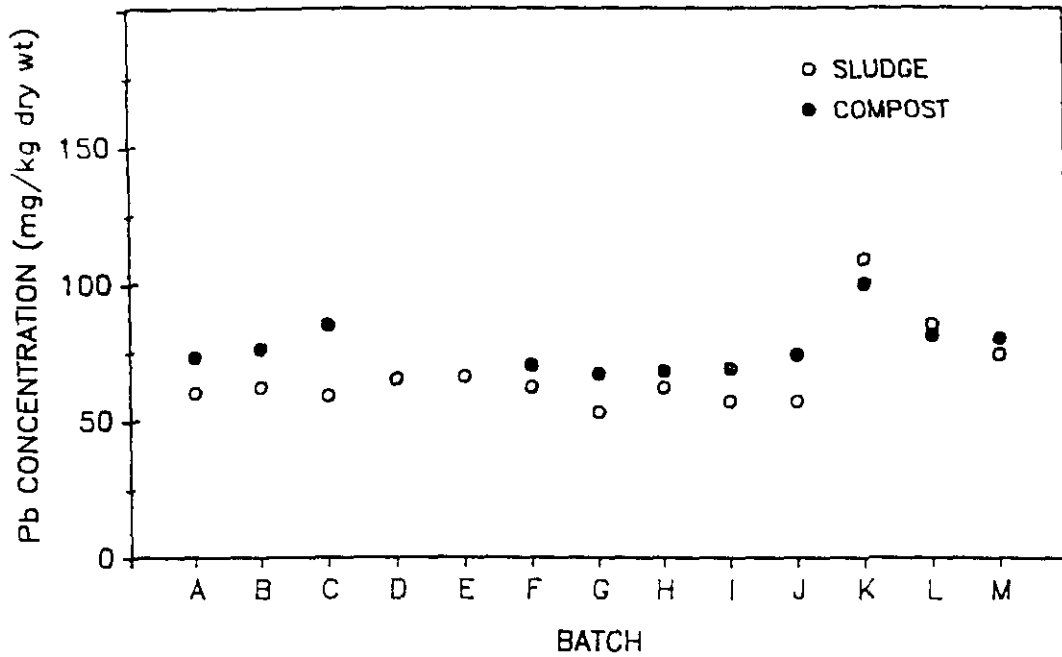
FIGURE 8 AVERAGE (± STD ERROR) LEAD CONCENTRATIONS IN
SLUDGE AND BATCH COMPOST SAMPLES
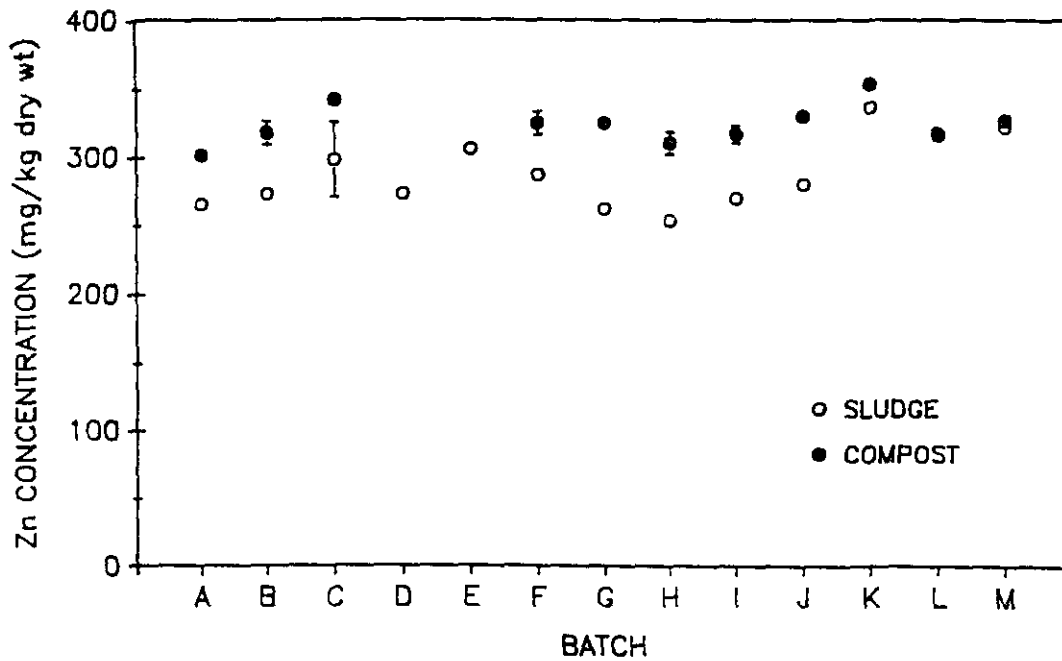


FIGURE 9 AVERAGE (± STD ERROR) ZINC CONCENTRATIONS IN
SLUDGE AND BATCH COMPOST SAMPLES

43 mg/kg (Type III classification, see Appendix A) to 15 mg/kg (Type II). The average cadmium concentration in the batch compost varied from 49 mg/kg to 30 mg/kg (Type III). The average nickel concentration in the sludge varied from 269 mg/kg (Type III) to 177 mg/kg (Type I). The average nickel concentration in the batch compost varied from 236 mg/kg (Type III) to 175 mg/kg (Type I). The average concentrations of the other four metals studied were within the limits of Type I material at all times.

The average total solids content of the sludge varied from 14.61 to 17.48 percent during the study period. The average volatile solids content of the batch compost varied from 38.81 to 43.16 percent.

In general, the metals concentrations in the sludge changed during composting. Cadmium, chromium and zinc concentrations in the batch compost were greater than or equal to those in the parent sludge. Lead concentrations in the batch compost were higher than those in the parent sludge in all but two batches in which they were lower. Copper concentrations in the batch compost were lower than in the parent sludge for for all batches. The concentrations of nickel in the batch compost were less than or equal to those in the parent sludge in ten of eleven batches. The batch to batch changes in metals concentrations followed similar trends in both sludge and batch compost.

The percent increase in metals concentrations during composting for each batch is presented in Figure 10. A positive

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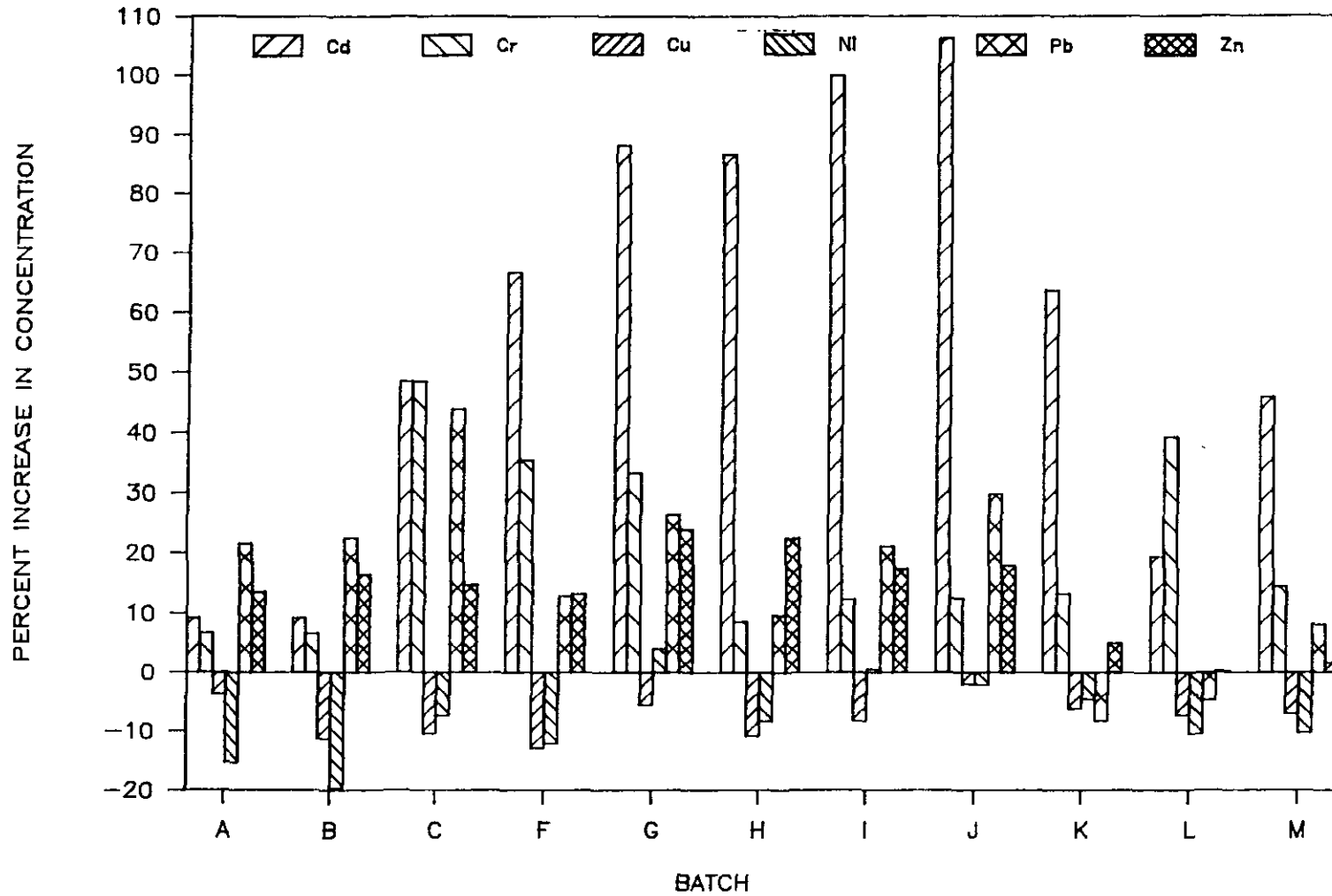
FIGURE 10  PERCENT INCREASE (+) OR DECREASE (−) IN SLUDGE METALS
CONCENTRATIONS DURING COMPOSTING

change denotes a higher metal concentration in the batch compost than in the parent sludge. A negative change indicates a decrease in the metal concentration during composting. Table 11 contains the mean and median values of the calculated percent changes in metals concentrations for each metal.

The change in metals concentration during composting differed for different metals. The percent increase in cadmium concentration increased from batch C to batch J and then decreased. This is opposite of the batch to batch changes in the actual cadmium concentrations in the sludge and compost. Although the percent increase in cadmium concentration was increasing in these batches, the actual change in concentration between sludge and compost only varied from 13 to 17 mg/kg.

The percent change in chromium concentrations during composting decreased from batch C through batch J and then increased. This is the opposite of the effect for cadmium. The magnitude of the change was less than for cadmium. It is not known if these two trends are related. There were no discernable patterns in the magnitudes of the change in concentrations of the other metals.

The percent increase of the cadmium concentration during composting was much greater than for the other metals. This effect may be due to the chemistry of the sludge-metal interactions. Another reason may be that the cadmium concentration in the sludge was much lower than the other metals,

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TABLE 11   MEAN AND MEDIAN VALUES OF PERCENT CHANGE IN
          SLUDGE METALS CONCENTRATIONS DURING COMPOSTING

| METAL | MEAN | MEDIAN |
|-------|------|--------|
| Cd | 58.5 | 63.6 |
| Cr | 21.0 | 13.3 |
| Cu | -7.8 | -7.3 |
| Ni | -7.8 | -8.3 |
| Pb | 16.7 | 21.1 |
| Zn | 13.3 | 14.8 |

making it more sensitive to changes measured on a percentage basis. The percent increase in the cadmium concentrations were five to ten times that of zinc, while the concentrations of zinc in the sludge were 10 to 20 times the concentrations of cadmium.

The systematic increase in concentration of some metals during composting while other metals decreased in concentration indicates that the change in metals concentrations is not due solely to gain or loss of total solids. There must be an actual loss of metals occurring from the compost piles. Several mechanisms of metals losses are possible. These are:

1. Methylation of the metals by microorganisms and loss by volatilization,

2. sorption of the metal onto the bulking agent and removal during screening, and

3. removal in the leachate from the compost pile.

No information was found in the literature to indicate that methylation occurs to any significant extent during composting. Sorption of metals onto the bulking agent was not investigated in this study. Analyses were conducted to determine if metals were removed via the leachate.

A sample of vacuum filtrate was collected from the sludge composted in batch A. A sample of leachate from batch H was collected. The results of the metals analyses of these liquid samples are presented in Table 12.

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TABLE 12   RESULTS OF METALS ANALYSES OF LIQUID SAMPLES

| BATCH | SAMPLE TYPE | METALS CONCENTRATION (mg/L) | | | | | |
|-------|-------------|------|------|------|------|------|------|
|       |             | Cd   | Cr   | Cu   | Ni   | Pb   | Zn   |
| A     | Filtrate    | 0.01 | nd   | 0.42 | 0.16 | nd   | 0.05 |
| H     | Leachate    | 0.01 | nd   | 0.17 | 0.40 | nd   | 0.13 |

nd- not detected

Both the filtrate and leachate samples contained copper and nickel. Concentrations of these metals decreased during composting of batch A and batch H. Both samples also contained cadmium and zinc. The concentrations of these metals increased during composting in batch A and batch H.

The concentrations of cadmium and zinc in the liquid samples were lower than those of copper and nickel. If the cadmium and zinc were being lost from the compost pile, the loss was probably small enough to be offset by the increase in concentration due to the degradation of total solids during composting. This would result in a net increase in the concentrations of these metals.

The metals in the liquid samples may be from the loss of metals during composting, or they may be due to metals that remain in the liquid portion throughout the treatment process. These metals may enter the liquid portion of the solid stream at several points in the treatment process:

1. In the activated sludge process
2. during sludge conditioning, and
3. during composting.

In the aeration basin, metals in solution are adsorbed onto sludge solids. The efficiency of this process is 30-98 percent, varying with the individual metal and the treatment plant. Some of the metals that remain in solution will be carried over into the solid stream in the pore water of the sludge. These metals could then be detected in the vacuum filtrate. If this was the

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only source of metals in the filtrate, then the concentrations would be the same as or lower than the metals in the plant's treated effluent. The addition of lime during conditioning would precipitate some of the metals, lowering the concentrations.

A sample of final effluent was not collected. The concentrations of the metals in the filtrate were compared to the metals concentrations in secondary effluents obtained from the literature and listed in Table 1. The concentrations of cadmium and zinc were within the ranges of values reported. The concentrations of copper and nickel were much higher than those reported.

Metals could enter the liquid fraction of the solid stream during sludge conditioning. As noted in chapter two, it is possible for metals to be displaced from the sludge by the addition of other cations. The sludge at this facility is conditioned with lime $(Ca(OH)_2)$. If the added calcium ions displaced metal ions from the sludge they would be those metals with the lower affinities for the sludge. Cheng et al. (1975) and Sterritt and Lester (1981b) reported that the order of affinity of metals for sludge is Cr>Cd>Ag>Pb>Zn>Cu>Ni, with some variation with pH. In the filtrate sample, copper and nickel were present at higher concentrations than cadmium and zinc. Chromium and lead were not detected.

The pH of the leachate was 11.5. At this pH, those metals detected in solution would be primarily in the form of anionic hydroxide complexes.

To determine if metals are lost during conditioning, a sample of unconditioned sludge was collected for analysis. The sludge was mechanically dewatered to 11 percent solids without chemical conditioning and analyzed for the study metals. The results are presented in Table 13. Also presented in Table 13 are the ranges of metals concentrations measured in the conditioned sludge collected during the batch composting study.

The concentrations of copper and nickel are much higher than in the conditioned sludge. The concentration of cadmium was approximately the same as the concentrations measured in the conditioned sludge. The concentration of chromium was approximately the same as the lower concentrations measured in the conditioned sludge. The concentrations of lead and zinc were slightly higher than those measured in the conditioned sludge samples.

Differences in metals concentrations between conditioned and unconditioned sludge could be due to loss of metals during conditioning. Another factor is the dilution of the sludge total solids by the lime added during conditioning. This facility adds lime at the rate of 20 percent by weight. This would result in a corresponding dilution of sludge constituents by the calcium solids.

TABLE 13   RESULTS OF METALS ANALYSIS OF UNCONDITIONED SLUDGE

| DATE | METALS CONCENTRATION (mg/kg dry wt) | | | | | |
|---|---|---|---|---|---|---|
| COLLECTED | Cd | Cr | Cu | Ni | Pb | Zn |
| 06/21 | 31 | 24 | 716 | 340 | 92 | 437 |
| Range measured in conditioned sludge | 13-48 | 34-134 | 392-587 | 148-284 | 46-128 | 236-372 |

The concentrations of nickel and zinc were higher in the leachate than in the filtrate. It is not completely justifiable to compare these two samples because they were collected from different batches of sludge. This difference however, may indicate that a loss of metals occurs from the sludge solids during composting. As the organic solids are degraded during composting, metals may be released from the adsorbtion sites and enter the liquid phase of the sludge. These soluble metals would be susceptible to loss from the pile via leaching.

Another factor is the change in pH during composting. The pH of the leachate was 5.7. At this pH, previously precipitated metals in the sludge could be resolublized.

If these were the only factors involved, then it would be expected that all the study metals would be detected in the liquid samples. Chromium and lead were not detected. The reason may be that as the metal ions are desorbed from the sludge some may re-adsorb displacing other ions on other adsorbtion sites. The net effect of this would be the loss of only those metals with lower affinities for the sludge.

## 4.2 STATISTICAL ANALYSIS

Statistical analysis of the data from the batch composting study was performed. The data was analyzed to determine if the differences in metals concentrations of the sludge and compost

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samples were statistically significant. First, a "t"-test (Student's t-distribution) was used to compare the differences in metals concentrations of the sludge and batch compost using the average concentrations for each batch. The probability that the differences were significant exceeded 99 percent.

Next, Analysis of Variance (ANOVA) was performed using the results of the individual samples analyses. Three analyses were performed. The differences between the sludge and batch compost metals concentrations were compared for all samples collected. Next, the differences in the metals concentrations were analyzed for both sludge and batch compost. Finally, a two-way analysis was performed to compare the batch to batch variability with the variability between sludge and batch compost metals concentrations.

The specific hypotheses tested and the results of the analyses are presented in Table 14. For comparisons of metals concentrations between sludge and compost, and between batches the significance of F (the probability that the hypothesis tested is true) was less than 0.001 for each metal. For the two way analysis, the significance of F was less than 0.03 for each metal.

Based on the results of the statistical analysis the following may be concluded:

1. The measured changes in metals concentrations between sludge and batch compost are significant.

TABLE 14   RESULTS OF ANALYSIS OF VARIANCE OF BATCH COMPOSTING DATA

SIGNIFICANCE OF F

| METAL | BATCH TO BATCH | SLUDGE VS COMPOST | COMBINED ANALYSIS |
|-------|----------------|-------------------|-------------------|
| Cd    | ***            | ***               | ***               |
| Cr    | ***            | ***               | ***               |
| Cu    | ***            | ***               | 0.023             |
| Ni    | ***            | ***               | ***               |
| Pb    | ***            | ***               | ***               |
| Zn    | ***            | ***               | 0.027             |

*** less than 0.001

HYPOTHESES TESTED:

(1)   The concentration of a metal measured in sludge samples in any batch are the same as those measured in compost samples for the same batch.

(2)   The concentration of a metal measured in sludge or compost samples in any batch are the same as those measured in samples in any other batch.

(3)   The ratio of the variation measured between sludge and compost samples to the variation measured between samples in different batches is less than or equal to the critical ratio (or the error mean square).

2.  Metals concentrations measured in samples in any batch
    are significantly different and distinct from those
    measured in any other batch.

3.  The effect of composting on sludge metals concentrations
    is significantly greater than the effect of those
    factors influencing batch to batch variations.


## 4.3 STORED COMPOST ANALYSES


Eighteen samples were collected from the curing pile on eight
occasions. Fifteen samples of stockpiled compost were collected
on five occasions. The volatile solids content of the stored
compost samples were between 34 and 39 percent. The results of
the metals analyses of these samples are presented in Appendix C,
Table C3. Qualitative comparisons were made between the metals
concentrations in the batch compost and the stored compost to
illustrate the variations in compost quality that can exist on-
site.

These results were reduced to average metals concentrations
for each type of sample on each day they were collected. These
average concentrations are listed in Appendix C, Table C4. These
values are also presented with the average metals concentrations
of the batch compost samples in Figures 11 through 16 (cadmium,
chromium, copper, nickel, lead and zinc, respectively). The
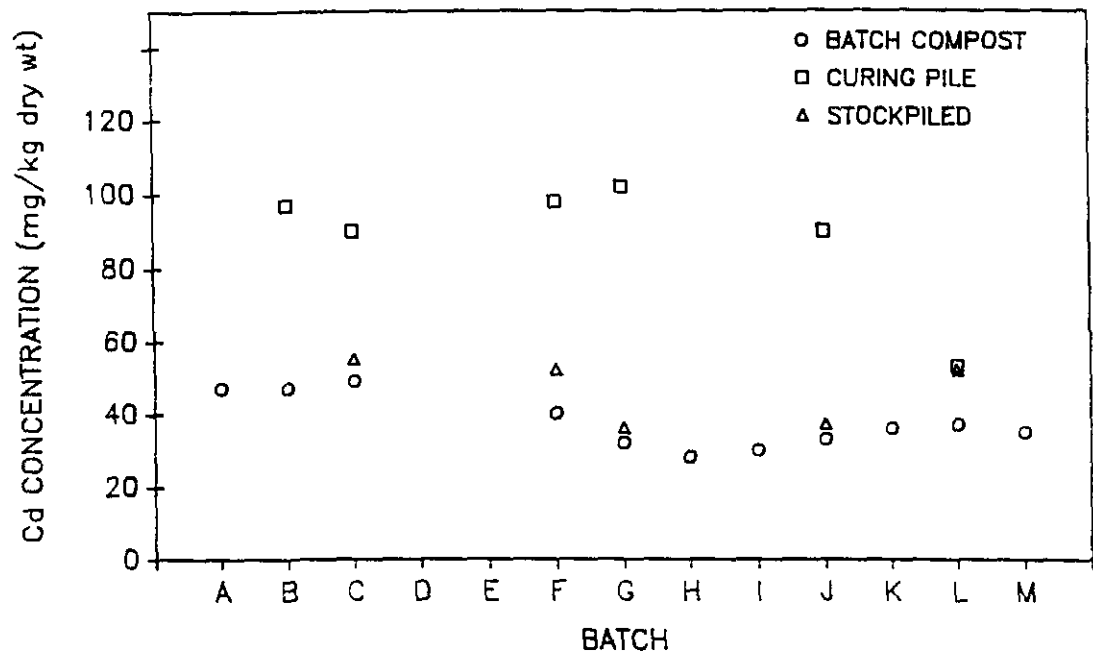
FIGURE 11 AVERAGE CADMIUM CONCENTRATIONS IN COMPOST SAMPLES
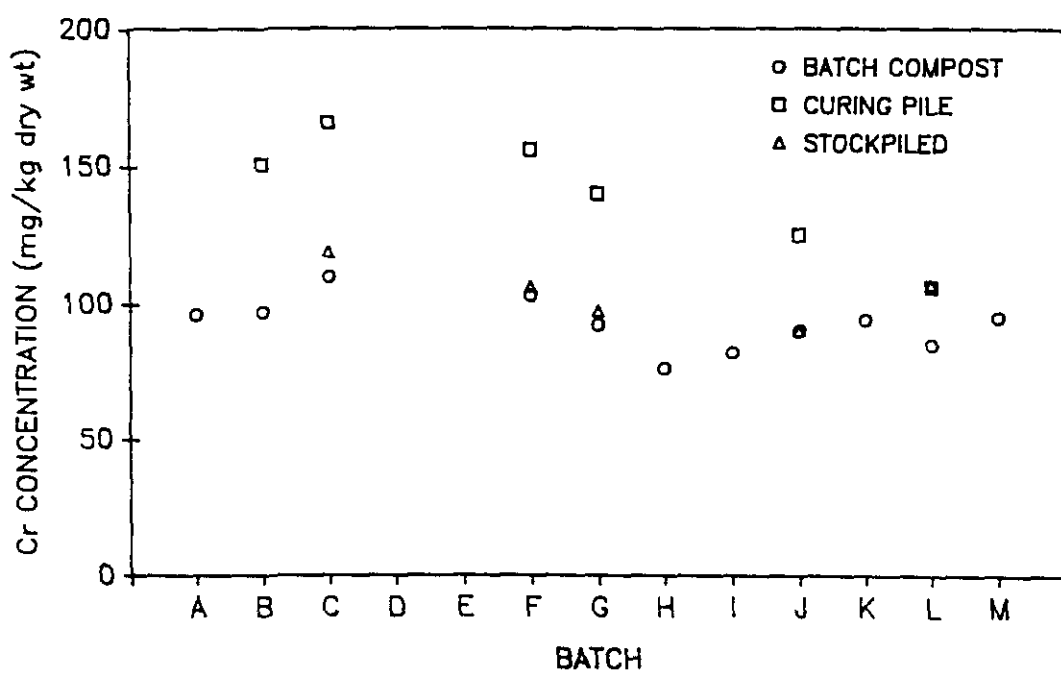


FIGURE 12 AVERAGE CHROMIUM CONCENTRATIONS IN COMPOST SAMPLES

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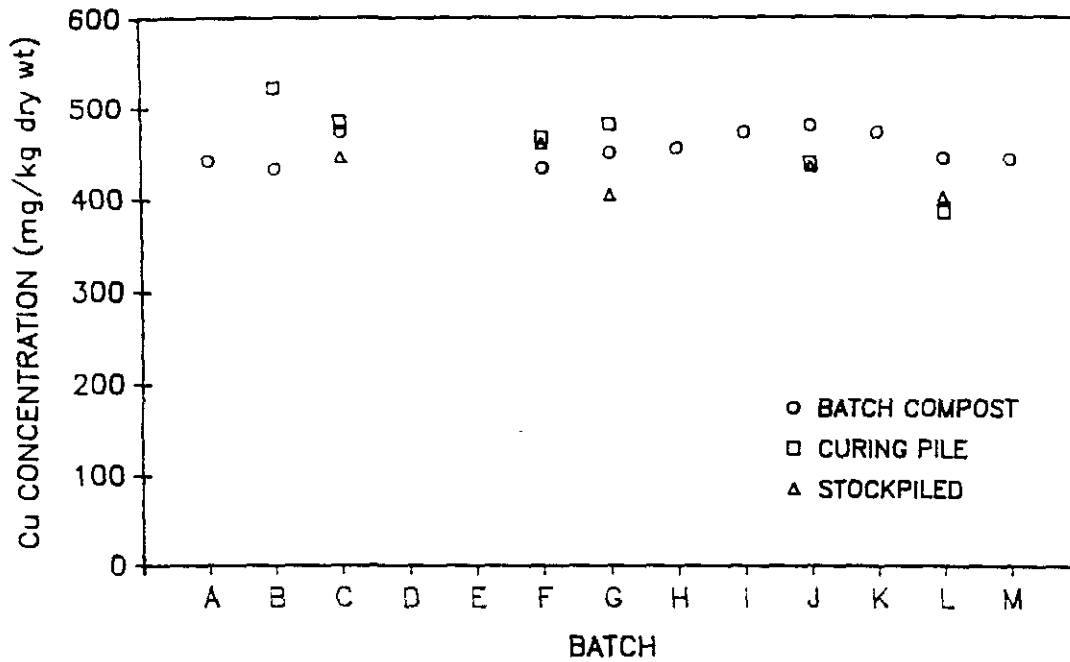
FIGURE 13  AVERAGE COPPER CONCENTRATIONS IN COMPOST SAMPLES
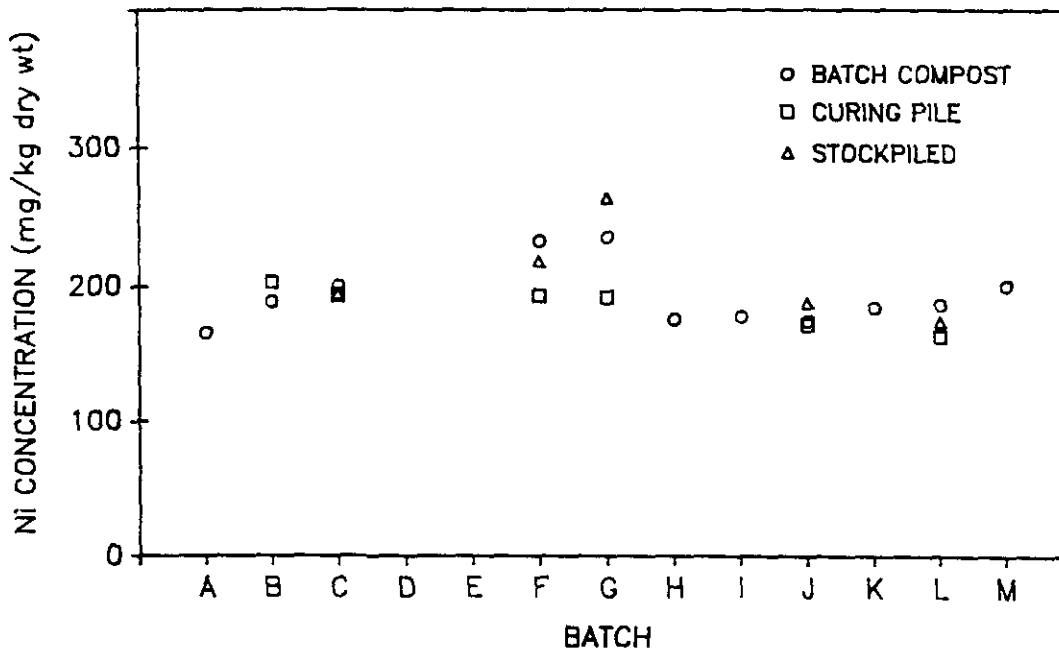


FIGURE 14  AVERAGE NICKEL CONCENTRATIONS IN COMPOST SAMPLES

84
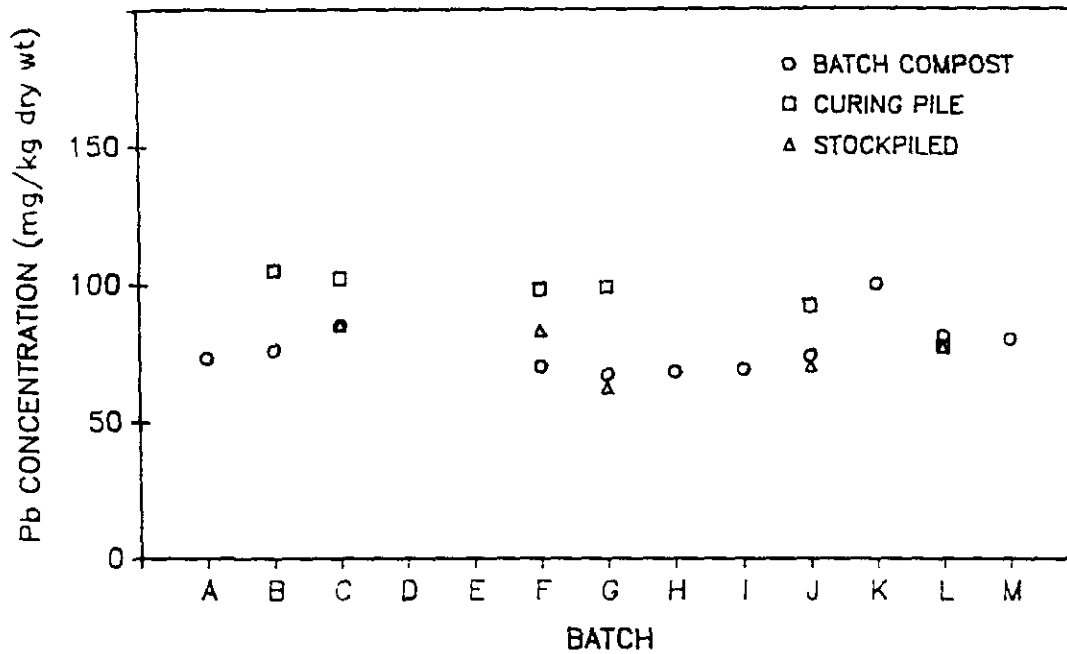
FIGURE 15  AVERAGE LEAD CONCENTRATIONS IN COMPOST SAMPLES
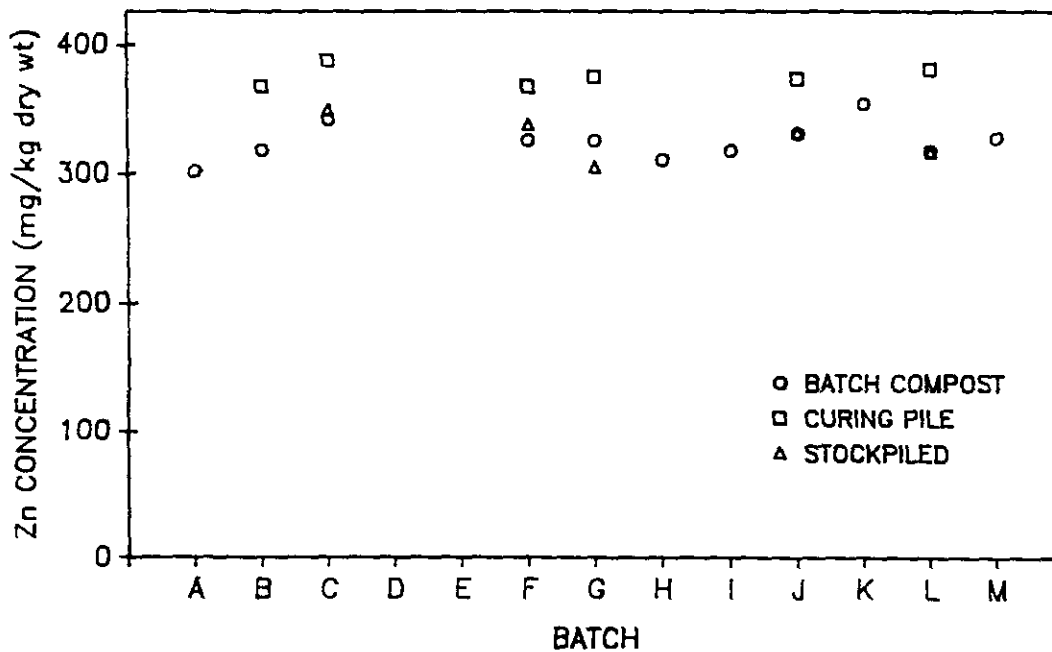


FIGURE 16  AVERAGE ZINC CONCENTRATIONS IN COMPOST SAMPLES

values for the stored compost samples are shown corresponding to those of the batch compost samples collected at approximately the same time. Table 15 contains the mean and median values of the percent differences in average metals concentrations between the batch and stored compost samples.

As the compost was stockpiled it was combined with the material from the previous batches. This compositing effect would be expected to reduce the variability of the of the metals concentrations in the stockpiled compost compared with the batch compost. The reduction in variability should increase the difference in the metals concentrations between the two sample types.

This effect is not noticeable in the data. In general, there appeared to be little difference between the metals concentrations of the stockpiled compost and the batch compost for all metals studied. With the exception of cadmium, average metals concentrations in the stockpiled compost samples were generally within 12 percent of the concentrations in the batch compost.

Since compost had not been added to the curing pile for several months prior to this study, the metals concentrations in the cured compost should reflect the metals concentrations in the batch compost of that prior period. The concentration of cadmium declined during the study period. This should increase the difference between the concentrations of the two sets of samples. Less of a difference would be expected for a metal such as copper,

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TABLE 15  PERCENT DIFFERENCE BETWEEN AVERAGE METALS CONCENTRATIONS
IN BATCH COMPOST AND STORED COMPOST SAMPLES

|  | PERCENT DIFFERENCE BETWEEN BATCH COMPOST AND | | | |
|  | STOCKPILED | | CURING PILE | |
| METAL | MEAN | MEDIAN | MEAN | MEDIAN |
| Cd | 22.0 | 13.8 | 130.2 | 106.9 |
| Cr | 8.9 | 5.4 | 46.0 | 50.8 |
| Cu | 8.4 | 9.5 | 9.9 | 7.6 |
| Ni | 7.0 | 6.9 | 10.1 | 6.9 |
| Pb | 7.5 | 5.2 | 29.7 | 25.2 |
| Zn | 8.0 | 2.3 | 15.3 | 13.7 |

which was much less variable during and presumably prior to the study period. This was observed.

The differences between the average metals concentrations of the compost from the curing pile and the batch compost varied with the metal studied. The concentrations of copper, nickel and zinc in the cured compost samples were within 21 percent of the batch compost concentrations. The concentrations of chromium and lead were generally within 55 percent of the batch compost concentrations. The concentrations of cadmium differed by as much as 224 percent from the batch compost concentrations. The greater differences in the cadmium concentrations is likely due to the lower concentrations in the influent raw wastewater during the study period because of the installation of pretreatment by the industrial user during the study period. Plant records indicate that cadmium concentrations in the parent sludge during the study period were lower than those in previously composted sludge.

## 4.4 VARIABILITY OF THE DATA

The variability of several subsets of the data from this study was measured by the coefficient of variation (CV). Coefficients of variation were calculated for several subsets of the data from the metals analyses, each for a different time interval. Coefficients of variation were also calculated for the percent changes in metals concentrations measured in the batch

composting study. The results are presented in Appendix D. Table D1 contains the CV's of the metals concentrations over the entire study period for each type of sample. Table D2 contains the CV's of the metals concentrations in the sludge samples for each day they were collected. Table D3 contains the CV's of the metals concentrations in the stockpiled compost samples for each day they were collected. Table D4 contains the CV's of the average metals concentrations in the sludge and batch compost from each batch composted. Table D5 contains the CV's of the average metals concentrations in the sludge and batch compost over the entire study period. Table D6 contains the CV's of the percent change in metals concentrations for each metal.

Variability was considered low if the CV was less than 25 percent. Variability was moderate if the CV was between 25 and 50 percent. If the CV was greater than 50 percent, then the variability was considered high (Sommers, 1976). No statistical analysis was performed to compare the variability of different sets of data.

The variability of the measured metals concentrations was low to moderate for all time periods. The daily CV's of the metals concentrations in the sludge samples (Table D2) ranged from 0 to 39 percent, but most values were less than ten percent. The CV's of the metals concentrations within each batch of sludge or batch compost (Table D4) was between 2 and 31 percent. Most of these values were less than ten percent as well.

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Variability of the metals concentrations increased over longer time periods. The CV's of the average metals concentrations for the entire study period (Table D5) was between 4 and 37 percent for sludge samples and between 4 and 20 percent for batch compost samples. The CV's of the metals concentrations in the sludge samples for the entire study period (Table D1) varied from 6 to 39 percent. The CV's of the metals concentrations in the batch compost samples for the entire study period (Table D1) varied from 6 to 22 percent.

In general, concentrations of lead and cadmium were more variable than the other metals. In those variability analyses that included data sets for both sludge and batch compost, the metals concentrations were more variable in the sludge than the batch compost.

The variability of the metals concentrations in the stored compost samples was about the same as that in the sludge or batch compost samples. The daily CV's of the metals concentrations in the stockpiled and curing pile samples (Table D3) were between 1 and 31 percent. The CV's were lower on days in the early part of the study than on days near the end of the study. The reason for this is not known. The CV's of the metals concentrations of the stockpiled compost samples for the entire study period (Table D1) were between 12 and 24 percent. The CV's of the metals concentrations in the curing pile samples (Table D1) were between 9 and 37 percent.

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The CV's of the change in metals concentrations were moderate to high for all metals. The CV for copper was 43 percent. The CV's for the other metals varied from 59 to 91 percent.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the results of this study, the following may be concluded:

1. The heavy metals concentrations in municipal sludge changed during composting. Typically, copper and nickel concentrations decreased while cadmium, chromium, lead, and zinc concentrations increased.

2. The changes in metals concentrations cannot be accounted for solely by changes in total solids. Other factors, such as degradation of organics, and loss of metals from the composting sludge via leaching must be involved.

3. The variability of the metals concentrations in the sludge and batch compost were typically low while the variability of the observed changes in sludge metals concentrations during composting were high (CV greater than 50 percent) for most metals studied.

4. Some heavy metals are removed from the sludge in the the liquid fraction during dewatering and composting (via leaching).

## 5.2 RECOMMENDATIONS

It is recommended that further study in this area be conducted to determine:

1. The impact of individual factors on the change in metals concentrations in sludge during composting. These factors include degradation of organics, organic supplementation from amendments, metal-amendment interactions, and loss of metals through desorbtion and leaching.

2. The process parameters of wastewater treatment and sludge disposal that influence these factors.

3. The feasibility of modification of these parameters to change the quality of the final sludge compost.

4. The impact of these changes in concentrations on the accuracy of compost sampling programs and on projections of compost quality.

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APPENDIX A

SUMMARY OF SELECTED STATES' REGULATIONS ON LAND APPLICATION

Connecticut

Regulating Agency: Department of Environmental Protection
Type of Rules: Guidelines
Type of Approval Required: Site approval
Typical Interval Between Sludge Analyses: 3 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application
Criteria for Metals Regulations: Maximum permissible metals
concentrations, maximum cumulative loading limits
(See Table A1)


Delaware

Regulating Agency: Department of Natural Resources and
Environmental Control
Type of Rules: Draft regulations (published May, 1987)
Type of Approval Required: Site Approval
Typical Interval Between Sludge Analyses: 4 months
Metals Regulated: Cd, Cr, Cu, Ni, Pb, Hg, Zn
Disposal Options Specified: Agricultural use, land reclamation,
surface land disposal, and sludge distribution
Criteria for Metals Regulations: Land application must conform to
federal regulations and guidelines.  Maximum sludge metals
concentrations set for sludge distribution (table A2)


Maine

Regulating Agency: Department of Environmental Protection
Type of Rules: Regulations
Type of Approval Required: Site approval or program approval
Typical Interval Between Sludge Analyses: 1,3 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Criteria for Metals Regulation: Maximum Permissible Concentrations
(Table A3) and Maximum cumulative loading (Table A4)

Table A1   Connecticut Sludge Metals Limitations

| Metal | Maximum Permissible Concentration (mg/kg) | Maximum Cumulative Loading (kg/ha) |
|---|---|---|
| Cd | 25 | 3.37 |
| Cr | 1000 | 336.8 |
| Cu | 1000 | 84.2 |
| Pb | 1000 | 336.8 |
| Hg | 10 | not regulated |
| Ni | 200 | 33.7 |
| Zn | 2500 | 168.4 |

Table A2   Delaware Maximum Sludge Metals Concentrations for Sludge Distribution (mg/kg)

| | |
|---|---|
| Cd | 12.5 |
| Cu | 500 |
| Pb | 500 |
| Hg | 5 |
| Ni | 100 |
| Zn | 1250 |

Table A3   Maine Maximum Permissible Sludge Metals Concentrations   (mg/kg)

| | |
|---|---|
| Cd | 10 |
| Cr | 1000 |
| Cu | 1000 |
| Pb | 700 |
| Hg | 10 |
| Ni | 200 |
| Zn | 2000 |

Table A4   Maine Maximum Cumulative Metals Loading   (kg/ha)

| | Soil Cation Exchange Capacity | | |
|---|---|---|---|
| | ≤5 | 5-15 | ≥15 |
| Cd | 2.5 | 5 | 5 |
| Cr | 250 | 500 | 1000 |
| Cu | 125 | 250 | 500 |
| Pb | 500 | 1000 | 2000 |
| Ni | 250 | 500 | 1000 |
| Zn | 50 | 100 | 200 |

## Massachusetts

Regulating Agency: Department of Environmental Protection
Type of Rules: Regulations
Type of Approval Required: Site approval required for Type II and
Type III sludges
Typical Interval Between Sludge Analyses:1, 3 or 6 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn, Mo, B
Disposal Options Specified: Land application and distribution
Criteria for Metals regulation: Sludge classified Type I, II or
III by metals concentrations (Table A5). Type II and III subject
to maximum cumulative loading limits (Table A6), maximum annual
cadmium loading and maximum annual soil lead concentration.


## New Hampshire

Regulating Agency: Department of Environmental Services
Type of Rules: Regulations and guidelines
Type of Approval Required: Site approval required (except for
small scale manual application).
Typical Interval Between Sludge Analyses: 4 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Agricultural use, land reclamation,
forest application, governmental use, composting and landfilling
Criteria for Metals Regulations: Maximum permissible concentration
for agricultural use (Table A7), maximum lifetime loading rate for
agricultural use (Table A8), reclaimed land, highway buffer zones
and forested land (Table A9) and maximum annual cadmium loading.


## New Jersey

Regulating Agency: Department of Environmental Protection
Type of Rules: Regulations
Type of Approval Required: Permit required
Typical Interval Between Sludge Analyses: 1,3,6 or 12 months
Metals Regulated: As, Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified:Land application, composting and
landfiling
Criteria for Metals Regulation: Maximum permissible concentrations
(Class A sludge can be applied to a site for 40 years and Class B
sludge can be applied for 20 years before cumulative load limits
are reached) (Table A10)

Table A5   Massachusetts Sludge Classification Criteria
           (mg/kg)

|    | Type I | Type II | Type III |
|----|--------|---------|----------|
| Cd | <2     | 25      | >Type II |
| Cr | <1000  | 1000    | >Type II |
| Cu | <1000  | 1000    | >Type II |
| Ni | <200   | 200     | >Type II |
| Pb | <300   | 1000    | >Type II |
| Hg | <10    | 10      | >Type II |
| Zn | <2500  | 2500    | >Type II |
| Mo | <10    | 10      | >Type II |
| B  | <300   | 300     | >Type II |

Table A6   Massachusetts Maximum Cumulative Metals Loadings
           (lb/ac)

| | Soil Cation Exchange Capacity (meq/100g) | |
|----|----|----|
|    | ≤5  | ≥5  |
| Cd | 2   | 25  |
| Cu | 125 | 250 |
| Ni | 50  | 100 |
| Zn | 250 | 500 |

Table A7   New Hampshire Maximum Permissible Metals
           Concentrations for Agricultural Use   (mg/kg)

| | |
|----|------|
| Cd | 10   |
| Cr | 1000 |
| Cu | 1000 |
| Pb | 700  |
| Hg | 10   |
| Ni | 200  |
| Zn | 2000 |

Table A8 New Hampshire Maximum Lifetime Application Rate
         for Agricultural Use  (lb/ac)

| | Soil Cation Exchange Capacity | | |
| | ≤5 | 5-15 | ≥15 |
|---|---|---|---|
| Cd | 2.2 | 4.5 | 9 |
| Cr | 125 | 250 | 500 |
| Cu | 125 | 250 | 500 |
| Pb | 500 | 1000 | 2000 |
| Hg | 0.5 | 1 | 2 |
| Ni | 50 | 100 | 200 |
| Zn | 250 | 500 | 1000 |

Table A9 New Hampshire Maximum Lifetime Application Rates
         (lb/ac)

| | Highway Buffer Zones | Reclaimed Land | Forested Land |
|---|---|---|---|
| Cd | 9 | 4.5 | 4.5 |
| Cr | 500 | 250 | 250 |
| Cu | 500 | 250 | 250 |
| Pb | 2000 | 1000 | 1000 |
| Hg | 2 | 1 | 1 |
| Ni | 200 | 100 | 100 |
| Zn | 1000 | 500 | 500 |

Table A10 New Jersey Maximum Permissible Metals
          Concentrations (mg/kg)

| | Class A | Class B |
|---|---|---|
| Cd | 20 | 40 |
| Cr | 600 | 1200 |
| Pb | 2400 | 4800 |
| Ni | 625 | 1250 |
| Zn | 1200 | 1200 |
| Cr | 1000 | 1000 |
| Hg | 10 | 10 |
| As | 10 | 10 |

New York

Regulating Agency: Department of Environmental Conservation
Type of Rules: Regulations and Guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: 1,3 or 6 months for land
application and weekly, monthly or semiannually for composting and
distribution
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Agricultural use, land reclamation,
other vegetative covers and composting and distribution
Criteria for Metals Regulation: Maximum permissible concentration
for land application (Table A11), maximum permissible
concentration for composting and distribution (Table A12),
cumulative loading limits for land application (Table A13) and
annual cadmium loading limits


Pennsylvania

Regulating Agency: Bureau of Waste Management
Type of Rules: Proposed Regulations (published June, 1987)
Type of Approval Required: Site approval required for land
application.  Program approval required for composting.
Typical Interval Between Sludge Analyses: 4 months
Disposal Options Specified: Agricultural use, land reclamation,
land disposal and composting and distribution
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Criteria for Metals Regulation: None specified


Vermont

Regulating Agency: Agency of Natural Resources
Type of Rules: Guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: 6 or 12 months
Metals Regulated: Cd, Cr, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application and landfilling
Criteria for Metals Regulation: Maximum Permissible Concentrations
(Table A14)

Table A11    New York Maximum Permissible Metals
             Concentrations for Land Application
             (mg/kg)

| | |
|---|---|
| Cd | 25 |
| Cr | 1000 |
| Cu | 1000 |
| Pb | 1000 |
| Hg | 10 |
| Ni | 200 |
| Zn | 2500 |

Table A12    New York Maximum Permissible Metals
             Concentrations for Composting and Distribution
             (mg/kg)

| | |
|---|---|
| Cd | 10 |
| Cr | 1000 |
| Cu | 1000 |
| Pb | 250 |
| Hg | 10 |
| Ni | 200 |
| Zn | 2500 |

Table A13    New York Cumulative Metals Loading Limits
             (kg/ha)

| | |
|---|---|
| Cd | 5 |
| Cu | 125 |
| Pb | 500 |
| Ni | 50 |
| Zn | 250 |

Table A14    Vermont Maximum Permissible Metals Concentrations
             (mg/kg)

| | |
|---|---|
| Cd | 25 |
| Cr | 1000 |
| Cu | 1000 |
| Pb | 1000 |
| Hg | 10 |
| Ni | 200 |
| Zn | 2500 |

<u>Virginia</u>

Regulating Agency: State Water Control Board
Type of Rules: Regulations and guidelines
Type of Approval Required: Site approval required
Typical Interval Between Sludge Analyses: not specified
Metals Regulated: B, Cd, Cu, Pb, Hg, Ni, Zn
Disposal Options Specified: Land application and land reclamation
Criteria for Metals Regulation: Maximum permissible concentrations
(Table A15) and maximum cumulative loading guidelines

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Table A15   Virginia Maximum Permissible Metals Concentration
(mg/kg)

| | |
|---|---|
| B | 100 |
| Cd | 25 |
| Cu | 1000 |
| Pb | 1000 |
| Hg | 15 |
| Ni | 200 |
| Zn | 2500 |

APPENDIX B

ATOMIC ABSORPTION SPECTROPHOTOMETRY ANALYTICAL CONDITIONS

TABLE B1    ATOMIC ABSORPTION SPECTROPHOTOMETER OPERATING CONDITIONS

| Element | Wavelength (nm) | Atomizer | Fuel/ Oxidant | Linear Range (mg/l) | Sensitivity (mg/l) | Detection Limit (mg/l) (3) |
|---------|-----------------|----------|---------------|---------------------|---------------------|-----------------------------|
| Cd | 228.8 | flame (lean) | Ac/Air (1) | 0 to 2.0 | 0.028 | 0.005 |
| Cr | 357.9 | flame (rich) | Ac/Air | 0 to 5.0 | 0.078 | 0.005 |
| Cu | 324.8 | flame (lean) | Ac/Air | 0 to 5.0 | 0.077 | 0.005 |
| Ni | 341.5 | flame (lean) | Ac/Air | 0 to 20.0 | 0.40 | 0.004 |
| Pb | 217.0 (2) | flame (lean) | Ac/Air | 0 to 20.0 | 0.19 | 0.01 |
| Zn | 213.9 | flame (lean) | Ac/Air | 0 to 1.0 | 0.018 | 0.0008 |

(1) Acetylene/Air
(2) Background correction used
(3) Under operating conditions employed

1.11

TABLE B2   METALS CONCENTRATIONS IN PREPARED STANDARDS FOR ATOMIC
          ABSORPTION SPECTROPHOTOMETRY (mg/1)

| Metal | Standard No. 1 | 2 | 3 | 4 |
|-------|------|------|------|------|
| Cadmium | 0.4 | 1.0 | 2.0 | 4.0 |
| Chromium | 0.4 | 1.0 | 2.0 | 4.0 |
| Copper | 1.4 | 3.5 | 7.0 | 14.0 |
| Nickel | 0.6 | 1.5 | 3.0 | 6.0 |
| Lead | 0.2 | 0.5 | 1.0 | 2.0 |
| Zinc | 0.202 | 0.505 | 1.01 | 2.02 |

TABLE B3   RESULTS OF QC SAMPLE ANALYSES (mg metal/1)

| Sesssion No. | Cd | Cr | Cu | Ni | Pb | Zn |
|------|------|------|------|------|------|------|
| 1 | 0.85 | 1.72 | 11.71 | 2.86 | 1.19 | 1.147 |
| 2 | 0.88 | 1.46 | 10.96 | 2.75 | 1.10 | 1.140 |
| 3 | 0.86 | 1.62 | 10.90 | 2.80 | 1.13 | 1.122 |
| 4 | 0.86 | 1.43 | 10.78 | 2.75 | 1.04 | 1.125 |
| 5 | 0.86 | 1.44 | 11.30 | 2.88 | 1.03 | 1.118 |
| 6 | 0.85 | 1.14 | 11.30 | 2.89 | 1.15 | 1.111 |
| 7 | 0.86 | 1.38 | 11.19 | 2.89 | 1.11 | 1.083 |
| mean | 0.86 | 1.46 | 11.16 | 2.83 | 1.11 | 1.120 |
| std dev | 0.01 | 0.17 | 0.29 | 0.06 | 0.05 | 0.02 |
| % C of V | 1.08 | 11.70 | 2.61 | 2.08 | 4.80 | 1.72 |

APPENDIX C

DATA FROM HEAVY METALS ANALYSES

TABLE C1  RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Cr | Cu | Ni | Pb | Zn |
| A | 01/21/88 | S | 638 | 42 | 75 | 425 | 167 | 59 | 276 |
| A | 01/21 | S | 639 | 40 | 73 | 404 | 159 | 56 | 286 |
| A | 01/21 | S | 640 | 41 | 74 | 415 | 148 | 67 | 258 |
| A | 01/21 | S | 635 | 36 | 69 | 404 | 155 | 50 | 236 |
| A | 01/21 | S | 636 | 42 | 77 | 428 | 161 | 61 | 272 |
| A | 01/21 | S | 637 | 42 | 76 | 419 | 165 | 67 | 267 |
| A | 01/21 | S | 632 | 40 | 75 | 404 | 159 | 56 | 262 |
| A | 01/21 | S | 633 | 41 | 74 | 415 | 157 | 57 | 261 |
| A | 01/21 | S | 634 | 40 | 74 | 392 | 149 | 57 | 260 |
| A | 01/22 | S | 665 | 42 | 96 | 484 | 167 | 67 | 273 |
| A | 01/22 | S | 664 | 41 | 98 | 492 | 166 | 68 | 269 |
| A | 01/22 | S | 663 | 41 | 98 | 465 | 164 | 52 | 255 |
| A | 01/22 | S | 662 | 40 | 96 | 469 | 162 | 59 | 269 |
| A | 01/25 | S | 661 | 45 | 98 | 467 | 250 | 57 | 268 |
| A | 01/25 | S | 660 | 46 | 92 | 481 | 254 | 62 | 262 |
| A | 01/25 | S | 659 | 46 | 93 | 462 | 269 | 55 | 254 |
| A | 01/25 | S | 658 | 48 | 92 | 498 | 255 | 58 | 267 |
| | | | | | | | | | |
| A | 03/01 | C | 897 | 47 | 94 | 453 | 162 | 66 | 287 |
| A | 03/01 | C | 898 | 49 | 98 | 473 | 171 | 68 | 298 |
| A | 03/01 | C | 899 | 46 | 91 | 413 | 156 | 71 | 284 |
| A | 03/01 | C | 900 | 53 | 107 | 444 | 180 | 86 | 336 |
| A | 03/01 | C | 893 | 43 | 90 | 434 | 168 | 72 | 312 |
| A | 03/01 | C | 894 | 47 | 93 | 440 | 166 | 67 | 283 |
| A | 03/01 | C | 895 | 48 | 94 | 437 | 161 | 74 | 297 |
| A | 03/01 | C | 896 | 45 | 98 | 439 | 165 | 78 | 307 |
| | | | | | | | | | |
| B | 01/27 | S | 654 | 45 | 92 | 461 | 235 | 48 | 261 |
| B | 01/27 | S | 655 | 47 | 88 | 488 | 239 | 57 | 255 |
| B | 01/27 | S | 656 | 47 | 90 | 483 | 242 | 59 | 265 |
| B | 01/27 | S | 657 | 47 | 85 | 498 | 246 | 58 | 268 |
| B | 01/28 | S | 653 | 44 | 87 | 474 | 228 | 57 | 273 |
| B | 01/28 | S | 652 | 43 | 97 | 484 | 222 | 60 | 256 |
| B | 01/28 | S | 651 | 45 | 92 | 499 | 233 | 54 | 274 |
| B | 01/29 | S | 650 | 42 | 95 | 477 | 213 | 71 | 317 |
| B | 01/29 | S | 649 | 42 | 92 | 465 | 208 | 53 | 261 |
| B | 01/29 | S | 648 | 41 | 90 | 478 | 212 | 50 | 255 |
| B | 02/01 | S | 645 | 40 | 84 | 499 | 246 | 71 | 301 |

TABLE C1   RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|-------|----------------|----------|----------|----|----|----|----|----|----|
| B | 02/01 | S | 644 | 40 | 89 | 503 | 249 | 68 | 274 |
| B | 02/01 | S | 647 | 39 | 91 | 493 | 249 | 88 | 275 |
| B | 02/01 | S | 646 | 41 | 105 | 533 | 266 | 70 | 292 |
| B | 03/03 | C | 817 | 45 | 95 | 431 | 189 | 71 | 318 |
| B | 03/03 | C | 818 | 43 | 91 | 415 | 183 | 69 | 295 |
| B | 03/03 | C | 819 | 45 | 96 | 438 | 188 | 86 | 316 |
| B | 03/03 | C | 820 | 47 | 95 | 428 | 190 | 76 | 338 |
| B | 03/03 | C | 821 | 61 | 122 | 493 | 211 | 92 | 370 |
| B | 03/03 | C | 822 | 45 | 93 | 449 | 185 | 78 | 297 |
| B | 03/03 | C | 823 | 45 | 96 | 404 | 187 | 70 | 302 |
| B | 03/03 | C | 824 | 44 | 91 | 404 | 182 | 64 | 306 |
| C | 02/09 | S | 681 | 31 | 79 | 472 | 218 | 53 | 246 |
| C | 02/09 | S | 641 | 33 | 84 | 479 | 217 | 62 | 602 |
| C | 02/09 | S | 642 | 32 | 81 | 501 | 215 | 63 | 289 |
| C | 02/09 | S | 643 | 32 | 73 | 514 | 223 | 55 | 266 |
| C | 02/10 | S | 677 | 33 | 74 | 587 | 230 | 61 | 301 |
| C | 02/10 | S | 680 | 33 | 68 | 540 | 208 | 59 | 264 |
| C | 02/10 | S | 679 | 33 | 74 | 538 | 214 | 68 | 264 |
| C | 02/10 | S | 678 | 33 | 69 | 558 | 214 | 59 | 269 |
| C | 02/11 | S | 676 | 33 | 71 | 533 | 214 | 56 | 264 |
| C | 02/11 | S | 675 | 34 | 73 | 546 | 208 | 61 | 268 |
| C | 02/11 | S | 674 | 32 | 78 | 523 | 211 | 57 | 258 |
| C | 02/11 | S | 673 | 34 | 69 | 557 | 214 | 58 | 284 |
| C | 03/15 | C | 808 | 49 | 112 | 506 | 208 | 86 | 346 |
| C | 03/15 | C | 809 | 48 | 109 | 467 | 202 | 79 | 352 |
| C | 03/15 | C | 810 | 42 | 99 | 419 | 177 | 77 | 313 |
| C | 03/15 | C | 814 | 49 | 114 | 489 | 207 | 84 | 341 |
| C | 03/15 | C | 811 | 64 | 132 | 487 | 209 | 97 | 372 |
| C | 03/15 | C | 812 | 42 | 102 | 474 | 194 | 77 | 340 |
| C | 03/15 | C | 813 | 51 | 111 | 503 | 210 | 97 | 332 |
| C | 03/15 | C | 815 | 45 | 99 | 449 | 191 | 82 | 336 |
| D | 02/19 | S | 672 | 27 | 74 | 534 | 203 | 69 | 274 |
| D | 02/19 | S | 671 | 28 | 76 | 546 | 215 | 61 | 285 |
| D | 02/19 | S | 670 | 27 | 77 | 535 | 212 | 62 | 268 |

TABLE C1  RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES  (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|-------|----------------|----------|----------|----|----|-----|-----|----|-----|
| D | 02/22 | S | 669 | 27 | 70 | 530 | 275 | 64 | 282 |
| D | 02/23 | S | 1001 | 25 | 69 | 518 | 263 | 64 | 270 |
| D | 02/23 | S | 1002 | 24 | 75 | 518 | 258 | 69 | 261 |
| D | 02/23 | S | 1003 | 24 | 73 | 530 | 268 | 69 | 273 |
| D | 02/23 | S | 1004 | 28 | 75 | 519 | 261 | 67 | 268 |
| D | 02/24 | S | 1005 | 27 | 72 | 528 | 260 | 62 | 268 |
| D | 02/24 | S | 1006 | 29 | 78 | 541 | 262 | 66 | 276 |
| D | 02/24 | S | 1007 | 28 | 74 | 553 | 253 | 67 | 272 |
| D | 02/24 | S | 1008 | 29 | 76 | 538 | 254 | 63 | 281 |
| E | 03/01 | S | 1009 | 27 | 73 | 516 | 268 | 62 | 297 |
| E | 03/01 | S | 1010 | 29 | 78 | 528 | 268 | 72 | 287 |
| E | 03/01 | S | 1012 | 26 | 76 | 539 | 273 | 64 | 306 |
| E | 03/02 | S | 1013 | 28 | 76 | 546 | 268 | 75 | 306 |
| E | 03/02 | S | 1014 | 27 | 76 | 529 | 270 | 67 | 303 |
| E | 03/02 | S | 1011 | 28 | 76 | 544 | 271 | 64 | 307 |
| E | 03/03 | S | 1015 | 26 | 77 | 542 | 281 | 69 | 326 |
| E | 03/03 | S | 1016 | 28 | 82 | 524 | 269 | 70 | 305 |
| E | 03/03 | S | 1017 | 47 | 83 | 518 | 258 | 62 | 297 |
| E | 03/03 | S | 1018 | 25 | 75 | 499 | 268 | 62 | 321 |
| E | 03/04 | S | 1019 | 27 | 84 | 532 | 272 | 62 | 300 |
| E | 03/04 | S | 1020 | 27 | 87 | 524 | 263 | 67 | 317 |
| E | 03/04 | S | 1021 | 25 | 84 | 522 | 271 | 67 | 301 |
| F | 03/07 | S | 1022 | 24 | 75 | 491 | 275 | 59 | 296 |
| F | 03/07 | S | 1023 | 23 | 77 | 478 | 268 | 67 | 281 |
| F | 03/07 | S | 1024 | 22 | 79 | 495 | 267 | 60 | 293 |
| F | 03/07 | S | 1025 | 24 | 81 | 505 | 271 | 61 | 284 |
| F | 03/08 | S | 628 | 23 | 69 | 500 | 273 | 60 | 278 |
| F | 03/08 | S | 629 | 23 | 76 | 499 | 253 | 58 | 243 |
| F | 03/08 | S | 630 | 25 | 80 | 498 | 277 | 70 | 328 |
| F | 03/08 | S | 631 | 24 | 81 | 497 | 284 | 59 | 282 |
| F | 03/09 | S | 625 | 23 | 79 | 490 | 275 | 63 | 288 |
| F | 03/09 | S | 626 | 23 | 79 | 501 | 270 | 64 | 291 |
| F | 03/09 | S | 627 | 22 | 78 | 517 | 265 | 60 | 303 |
| F | 03/10 | S | 624 | 21 | 72 | 497 | 248 | 61 | 280 |
| F | 03/10 | S | 621 | 34 | 76 | 504 | 250 | 65 | 273 |
| F | 03/10 | S | 622 | 22 | 73 | 508 | 256 | 67 | 290 |

TABLE C1  RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|-------|----------------|----------|----------|-----|-----|-----|-----|-----|-----|
| | | | | | | METALS CONCENTRATIONS (mg/kg dry wt.) | | | |
| F | 03/10 | S | 623 | 20 | 71 | 484 | 248 | 61 | 289 |
| F | 04/13 | C | 882 | 38 | 93 | 468 | 243 | 69 | 326 |
| F | 04/13 | C | 883 | 38 | 96 | 463 | 241 | 73 | 323 |
| F | 04/13 | C | 884 | 37 | 103 | 448 | 232 | 69 | 350 |
| F | 04/13 | C | 885 | 38 | 93 | 445 | 229 | 68 | 309 |
| F | 04/13 | C | 875 | 35 | 97 | 449 | 240 | 70 | 301 |
| F | 04/13 | C | 876 | 34 | 103 | 313 | 198 | 56 | 289 |
| F | 04/13 | C | 877 | 43 | 101 | 471 | 244 | 69 | 338 |
| F | 04/13 | C | 878 | 55 | 134 | 415 | 234 | 82 | 363 |
| G | 03/18 | S | 1026 | 16 | 61 | 459 | 221 | 51 | 297 |
| G | 03/18 | S | 1027 | 17 | 77 | 479 | 238 | 56 | 254 |
| G | 03/18 | S | 1028 | 17 | 74 | 487 | 234 | 54 | 266 |
| G | 03/21 | S | 1029 | 18 | 76 | 448 | 235 | 51 | 260 |
| G | 03/21 | S | 1030 | 17 | 68 | 492 | 231 | 49 | 268 |
| G | 03/21 | S | 1031 | 18 | 71 | 478 | 242 | 54 | 255 |
| G | 03/22 | S | 1032 | 17 | 66 | 464 | 223 | 53 | 258 |
| G | 03/22 | S | 1033 | 18 | 67 | 511 | 246 | 57 | 279 |
| G | 03/22 | S | 1034 | 17 | 63 | 501 | 240 | 52 | 264 |
| G | 03/23 | S | 1035 | 16 | 62 | 459 | 216 | 53 | 267 |
| G | 03/23 | S | 1036 | 17 | 71 | 484 | 229 | 53 | 250 |
| G | 03/23 | S | 1037 | 16 | 69 | 473 | 223 | 46 | 251 |
| G | 03/24 | S | 1038 | 16 | 65 | 487 | 221 | 57 | 277 |
| G | 03/24 | S | 1039 | 16 | 69 | 491 | 225 | 51 | 252 |
| G | 03/24 | S | 1040 | 16 | 68 | 490 | 224 | 48 | 256 |
| G | 03/25 | S | 1041 | 17 | 69 | 463 | 207 | 54 | 268 |
| G | 03/25 | S | 1042 | 17 | 71 | 483 | 221 | 55 | 261 |
| G | 03/25 | S | 1043 | 18 | 70 | 447 | 209 | 55 | 239 |
| G | 04/27 | C | 858 | 32 | 90 | 443 | 222 | 66 | 305 |
| G | 04/27 | C | 859 | 31 | 91 | 458 | 226 | 69 | 328 |
| G | 04/27 | C | 860 | 30 | 92 | 452 | 226 | 65 | 306 |
| G | 04/27 | C | 861 | 30 | 90 | 424 | 215 | 67 | 344 |
| G | 04/27 | C | 862 | 32 | 94 | 463 | 235 | 73 | 340 |
| G | 04/27 | C | 863 | 33 | 92 | 438 | 230 | 62 | 346 |
| G | 04/27 | C | 864 | 33 | 91 | 458 | 233 | 66 | 316 |
| G | 04/27 | C | 865 | 32 | 96 | 472 | 302 | 66 | 312 |

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TABLE C1   RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | |
|-------|---------|------|--------|----|-----|-----|-----|----|-----|
| | | | | | Cr | Cu | Ni | Pb | Zn |
| H | 03/31 | S | 925 | 20 | 64 | 504 | 195 | 60 | 258 |
| H | 03/31 | S | 926 | 17 | 66 | 525 | 197 | 69 | 264 |
| H | 03/31 | S | 927 | 15 | 65 | 522 | 197 | 60 | 267 |
| H | 04/01 | S | 928 | 17 | 73 | 521 | 195 | 59 | 255 |
| H | 04/01 | S | 930 | 15 | 68 | 512 | 193 | 60 | 247 |
| H | 04/01 | S | 931 | 15 | 68 | 524 | 193 | 83 | 270 |
| H | 04/01 | S | 932 | 15 | 70 | 512 | 196 | 52 | 250 |
| H | 04/04 | S | 933 | 14 | 75 | 510 | 190 | 61 | 249 |
| H | 04/04 | S | 934 | 13 | 74 | 498 | 189 | 57 | 246 |
| H | 04/04 | S | 935 | 13 | 74 | 499 | 187 | 65 | 238 |
| H | 04/04 | S | 936 | 13 | 74 | 492 | 184 | 60 | 244 |
| H | 05/09 | C | 866 | 27 | 77 | 460 | 178 | 69 | 303 |
| H | 05/09 | C | 867 | 29 | 79 | 477 | 183 | 77 | 336 |
| H | 05/09 | C | 868 | 29 | 80 | 447 | 177 | 72 | 321 |
| H | 05/09 | C | 869 | 28 | 75 | 485 | 177 | 66 | 300 |
| H | 05/09 | C | 870 | 23 | 68 | 422 | 169 | 58 | 277 |
| H | 05/09 | C | 871 | 29 | 74 | 444 | 172 | 66 | 323 |
| I | 04/11 | S | 937 | 15 | 71 | 523 | 186 | 60 | 260 |
| I | 04/11 | S | 938 | 15 | 71 | 537 | 184 | 81 | 255 |
| I | 04/11 | S | 940 | 15 | 68 | 513 | 180 | 54 | 246 |
| I | 04/12 | S | 941 | 15 | 67 | 516 | 182 | 62 | 250 |
| I | 04/12 | S | 942 | 15 | 71 | 514 | 176 | 52 | 300 |
| I | 04/12 | S | 943 | 15 | 74 | 542 | 179 | 54 | 289 |
| I | 04/12 | S | 944 | 15 | 77 | 554 | 175 | 52 | 275 |
| I | 04/13 | S | 945 | 15 | 70 | 513 | 185 | 57 | 273 |
| I | 04/13 | S | 946 | 15 | 83 | 480 | 167 | 55 | 292 |
| I | 04/13 | S | 947 | 16 | 78 | 501 | 169 | 49 | 280 |
| I | 04/13 | S | 948 | 15 | 77 | 493 | 166 | 50 | 254 |
| I | 05/18 | C | 808 | 29 | 83 | 467 | 175 | 67 | 313 |
| I | 05/18 | C | 809 | 31 | 83 | 483 | 182 | 69 | 346 |
| I | 05/18 | C | 811 | 28 | 80 | 468 | 178 | 67 | 301 |
| I | 05/18 | C | 812 | 33 | 85 | 461 | 173 | 66 | 305 |
| I | 05/18 | C | 813 | 30 | 81 | 492 | 178 | 74 | 327 |
| I | 05/18 | C | 819 | 30 | 81 | 471 | 179 | 69 | 311 |

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TABLE C1  RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|-------|----------------|----------|----------|-----|------|------|------|------|------|
| J | 04/19 | S | 1044 | 17 | 74 | 501 | 172 | 55 | 291 |
| J | 04/19 | S | 1045 | 16 | 81 | 497 | 198 | 54 | 292 |
| J | 04/19 | S | 1046 | 16 | 83 | 508 | 200 | 64 | 279 |
| J | 04/19 | S | 1047 | 16 | 82 | 514 | 181 | 54 | 306 |
| J | 04/20 | S | 1049 | 15 | 79 | 491 | 170 | 52 | 287 |
| J | 04/20 | S | 1050 | 14 | 79 | 479 | 165 | 67 | 263 |
| J | 04/21 | S | 950 | 14 | 77 | 475 | 164 | 51 | 247 |
| J | 04/21 | S | 949 | 15 | 82 | 506 | 173 | 52 | 270 |
| J | 04/22 | S | 618 | 15 | 78 | 450 | 196 | 52 | 244 |
| J | 04/22 | S | 616 | 18 | 82 | 501 | 169 | 50 | 294 |
| J | 04/22 | S | 617 | 17 | 83 | 507 | 174 | 58 | 300 |
| J | 04/25 | S | 1052 | 19 | 79 | 464 | 165 | 51 | 254 |
| J | 04/25 | S | 1053 | 17 | 76 | 489 | 214 | 57 | 268 |
| J | 04/25 | S | 1054 | 17 | 84 | 475 | 165 | 84 | 306 |
| J | 04/25 | S | 1055 | 19 | 83 | 506 | 177 | 56 | 305 |
| J | 05/25 | C | 829 | 33 | 93 | 496 | 183 | 78 | 339 |
| J | 05/25 | C | 821 | 29 | 78 | 467 | 159 | 74 | 306 |
| J | 05/25 | C | 826 | 32 | 97 | 487 | 176 | 73 | 331 |
| J | 05/25 | C | 810 | 35 | 96 | 481 | 179 | 73 | 335 |
| J | 05/25 | C | 814 | 35 | 88 | 484 | 181 | 73 | 335 |
| J | 05/25 | C | 815 | 32 | 85 | 473 | 174 | 70 | 331 |
| K | 05/03 | S | 1059 | 17 | 83 | 502 | 184 | 113 | 351 |
| K | 05/03 | S | 1058 | 19 | 108 | 500 | 193 | 115 | 323 |
| K | 05/03 | S | 1057 | 16 | 82 | 480 | 178 | 124 | 338 |
| K | 05/03 | S | 1056 | 18 | 82 | 504 | 185 | 110 | 337 |
| K | 05/04 | S | 1060 | 18 | 78 | 504 | 187 | 110 | 349 |
| K | 05/04 | S | 1061 | 23 | 79 | 486 | 187 | 108 | 338 |
| K | 05/04 | S | 1062 | 19 | 84 | 477 | 189 | 116 | 335 |
| K | 05/04 | S | 1063 | 21 | 87 | 509 | 192 | 128 | 372 |
| K | 05/05 | S | 1064 | 31 | 75 | 584 | 207 | 97 | 337 |
| K | 05/05 | S | 1065 | 28 | 76 | 489 | 211 | 93 | 320 |
| K | 05/05 | S | 1066 | 27 | 77 | 506 | 201 | 95 | 313 |
| K | 05/05 | S | 1067 | 27 | 83 | 504 | 210 | 95 | 330 |
| K | 06/08 | C | 823 | 34 | 86 | 463 | 179 | 102 | 375 |
| K | 06/08 | C | 824 | 38 | 98 | 476 | 192 | 110 | 365 |

TABLE C1   RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|
| K | 06/08 | C | 841 | 36 | 101 | 486 | 189 | 103 | 357 |
| K | 06/08 | C | 817 | 35 | 95 | 465 | 181 | 97 | 346 |
| K | 06/08 | C | 820 | 37 | 97 | 467 | 186 | 92 | 340 |
| K | 06/08 | C | 831 | 35 | 89 | 479 | 182 | 98 | 339 |
| L | 05/11 | S | 1077 | 25 | 76 | 519 | 207 | 93 | 328 |
| L | 05/11 | S | 1073 | 44 | 76 | 542 | 214 | 99 | 334 |
| L | 05/11 | S | 1074 | 26 | 76 | 501 | 202 | 94 | 318 |
| L | 05/11 | S | 1075 | 30 | 90 | 499 | 227 | 96 | 333 |
| L | 05/12 | S | 953 | 27 | 61 | 483 | 205 | 83 | 331 |
| L | 05/12 | S | 951 | 34 | 60 | 481 | 203 | 83 | 327 |
| L | 05/12 | S | 952 | 38 | 35 | 481 | 202 | 100 | 318 |
| L | 05/13 | S | 954 | 24 | 44 | 436 | 190 | 67 | 294 |
| L | 05/13 | S | 955 | 35 | 72 | 475 | 202 | 85 | 308 |
| L | 05/13 | S | 956 | 48 | 34 | 476 | 196 | 75 | 319 |
| L | 05/16 | S | 957 | 22 | 55 | 453 | 215 | 77 | 295 |
| L | 05/16 | S | 958 | 26 | 56 | 448 | 214 | 74 | 305 |
| L | 05/16 | S | 959 | 26 | 58 | 449 | 218 | 74 | 302 |
| L | 05/16 | S | 960 | 28 | 61 | 482 | 225 | 86 | 305 |
| L | 06/21 | C | 848 | 38 | 88 | 459 | 197 | 86 | 331 |
| L | 06/21 | C | 847 | 34 | 85 | 432 | 184 | 79 | 313 |
| L | 06/21 | C | 846 | 35 | 74 | 424 | 175 | 73 | 299 |
| L | 06/21 | C | 845 | 38 | 87 | 454 | 186 | 83 | 316 |
| L | 06/21 | C | 844 | 38 | 85 | 455 | 190 | 85 | 318 |
| L | 06/21 | C | 830 | 39 | 89 | 446 | 187 | 81 | 324 |
| M | 05/20 | S | 1068 | 23 | 78 | 466 | 210 | 73 | 323 |
| M | 05/20 | S | 1069 | 20 | 87 | 457 | 212 | 77 | 309 |
| M | 05/20 | S | 1070 | 21 | 87 | 440 | 200 | 70 | 297 |
| M | 05/20 | S | 1071 | 21 | 91 | 465 | 209 | 75 | 312 |
| M | 05/23 | S | 961 | 23 | 96 | 448 | 221 | 79 | 324 |
| M | 05/23 | S | 962 | 40 | 35 | 480 | 231 | 63 | 316 |
| M | 05/23 | S | 963 | 20 | 36 | 458 | 224 | 62 | 325 |
| M | 05/24 | S | 965 | 24 | 86 | 513 | 225 | 72 | 312 |
| M | 05/24 | S | 966 | 23 | 96 | 494 | 240 | 81 | 331 |
| M | 05/24 | S | 967 | 23 | 108 | 520 | 245 | 84 | 335 |
| M | 05/24 | S | 964 | 24 | 114 | 522 | 245 | 82 | 354 |

TABLE C1  RESULTS OF SLUDGE AND BATCH COMPOST METALS ANALYSES  (cont'd)

| BATCH | DATE COLLECTED | TYPE (1) | SAMPLE # | Cd | Cr | Cu | Ni | Pb | Zn |
|-------|----------------|----------|----------|----|----|----|----|----|----|
| | | | | | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | |
| M | 06/29 | C | 874 | 34 | 96 | 468 | 194 | 75 | 331 |
| M | 06/29 | C | 873 | 32 | 90 | 434 | 193 | 80 | 310 |
| M | 06/29 | C | 872 | 35 | 95 | 431 | 199 | 81 | 324 |
| M | 06/29 | C | 832 | 36 | 92 | 452 | 206 | 79 | 326 |
| M | 06/29 | C | 883 | 36 | 101 | 446 | 206 | 81 | 334 |
| M | 06/29 | C | 885 | 36 | 96 | 431 | 210 | 83 | 337 |

(1) S  sludge
    C  compost
NOTE: All of the dates collected are in the year 1988.

TABLE C2   AVERAGE METALS CONCENTRATIONS IN SLUDGE AND BATCH
           COMPOST SAMPLES

| BIN | SAMPLE TYPE (1) | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|
|     |     | Cd | Cr | Cu | Ni | Pb | Zn |
| A | S | 43 | 90 | 459 | 196 | 60 | 265 |
|   | C | 47 | 96 | 442 | 166 | 73 | 301 |
| B | S | 43 | 91 | 488 | 235 | 62 | 273 |
|   | C | 47 | 97 | 433 | 189 | 76 | 318 |
| C | S | 33 | 74 | 529 | 216 | 59 | 298 |
|   | C | 49 | 110 | 474 | 200 | 85 | 342 |
| D | S | 27 | 74 | 533 | 249 | 65 | 273 |
|   | C | SAMPLES LOST | | | | | |
| E | S | 28 | 79 | 528 | 269 | 66 | 306 |
|   | C | SAMPLES LOST | | | | | |
| F | S | 24 | 76 | 498 | 265 | 62 | 287 |
|   | C | 40 | 103 | 434 | 233 | 70 | 325 |
| G | S | 17 | 69 | 478 | 227 | 53 | 262 |
|   | C | 32 | 92 | 451 | 236 | 67 | 325 |
| H | S | 15 | 70 | 511 | 192 | 62 | 253 |
|   | C | 28 | 76 | 456 | 176 | 68 | 310 |
| I | S | 15 | 73 | 517 | 177 | 57 | 270 |
|   | C | 30 | 82 | 474 | 178 | 69 | 317 |
| J | S | 16 | 80 | 491 | 179 | 57 | 280 |
|   | C | 33 | 90 | 481 | 175 | 74 | 330 |
| K | S | 22 | 83 | ·504 | 194 | 109 | 337 |
|   | C | 36 | 94 | 473 | 185 | 100 | 354 |
| L | S | 31 | 61 | 480 | 209 | 85 | 316 |
|   | C | 37 | 85 | 445 | 187 | 81 | 317 |
| M | S | 24 | 83 | 478 | 224 | 74 | 322 |
|   | C | 35 | 95 | 444 | 201 | 80 | 327 |

(1)   S  sludge

      C  compost

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TABLE C3  RESULTS OF METALS ANALYSES OF STORED COMPOST SAMPLES

| DATE COLLECTED | SAMPLE TYPE (1) | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cd | Cr | Cu | Ni | Pb | Zn |
| 01/21/88 | CP | 83 | 123 | 427 | 191 | 93 | 360 |
| 02/10 | CP | 95 | 165 | 508 | 196 | 98 | 371 |
| 03/01 | CP | 92 | 149 | 505 | 198 | 101 | 361 |
| | CP | 102 | 152 | 540 | 207 | 109 | 375 |
| 03/17 | CP | 85 | 145 | 495 | 200 | 98 | 386 |
| | CP | 95 | 186 | 472 | 185 | 105 | 390 |
| | SP | 61 | 131 | 451 | 199 | 90 | 369 |
| | SP | 43 | 101 | 422 | 183 | 74 | 288 |
| | SP | 62 | 126 | 465 | 200 | 91 | 391 |
| 04/12 | CP | 101 | 146 | 485 | 204 | 98 | 368 |
| | CP | 95 | 153 | 445 | 181 | 96 | 365 |
| | CP | 99 | 169 | 471 | 194 | 100 | 367 |
| | SP | 55 | 112 | 494 | 243 | 90 | 360 |
| | SP | 48 | 98 | 430 | 195 | 75 | 309 |
| | SP | 53 | 109 | 460 | 217 | 85 | 341 |
| 05/03 | CP | 100 | 140 | 459 | 185 | 102 | 363 |
| | CP | 105 | 139 | 495 | 197 | 97 | 385 |
| | CP | 102 | 142 | 492 | 195 | 99 | 376 |
| | SP | 40 | 96 | 469 | 311 | 70 | 364 |
| | SP | 37 | 95 | 462 | 315 | 68 | 377 |
| | SP | 31 | 100 | 280 | 167 | 48 | 211 |
| 05/23 | CP | 94 | 124 | 450 | 173 | 94 | 381 |
| | CP | 84 | 116 | 418 | 170 | 86 | 365 |
| | CP | 93 | 136 | 450 | 174 | 96 | 378 |
| | SP | 36 | 92 | 428 | 187 | 68 | 333 |
| | SP | 37 | 87 | 447 | 192 | 71 | 335 |
| | SP | 37 | 90 | 432 | 184 | 70 | 326 |
| 06/21 | CP | 69 | 130 | 440 | 184 | 94 | 493 |
| | CP | 49 | 99 | 380 | 161 | 72 | 318 |
| | CP | 40 | 90 | 337 | 143 | 66 | 332 |
| | SP | 48 | 97 | 419 | 181 | 78 | 321 |
| | SP | 66 | 118 | 428 | 181 | 86 | 342 |
| | SP | 41 | 106 | 360 | 159 | 67 | 285 |

(1) CP   curing pile
    SP   stockpiled

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TABLE C4   AVERAGE METALS CONCENTRATIONS IN STORED COMPOST SAMPLES

| DATE COLLECTED | SAMPLE TYPE (1) | METALS CONCENTRATIONS (mg/kg dry wt.) | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | Cd | Cr | Cu | Ni | Pb | Zn |
| 01/21/88 | CP | 83 | 123 | 427 | 191 | 93 | 360 |
| 02/10 | CP | 95 | 165 | 508 | 196 | 98 | 371 |
| 03/01 | CP | 97 | 151 | 523 | 203 | 105 | 368 |
| 03/17 | CP | 90 | 166 | 484 | 193 | 102 | 388 |
| | SP | 55 | 119 | 446 | 194 | 85 | 349 |
| 04/12 | CP | 98 | 156 | 467 | 193 | 98 | 367 |
| | SP | 52 | 106 | 461 | 218 | 83 | 337 |
| 05/03 | CP | 102 | 140 | 482 | 192 | 99 | 375 |
| | SP | 36 | 97 | 404 | 264 | 62 | 317 |
| 05/23 | CP | 90 | 125 | 439 | 172 | 92 | 375 |
| | SP | 37 | 90 | 436 | 188 | 70 | 331 |
| 06/21 | CP | 53 | 106 | 386 | 163 | 77 | 381 |
| | SP | 52 | 107 | 402 | 174 | 77 | 416 |

(1) CP   curing pile
    SP   stockpiled

APPENDIX D

COEFFICIENTS OF VARIATION OF METALS ANALYSES DATA

TABLE D1   COEFFICIENTS OF VARIATION OF METALS CONCENTRATIONS IN
           SAMPLES (STUDY PERIOD)

| SAMPLE TYPE | COEFFICIENT OF VARIATION (Percent) | | | | | |
|---|---|---|---|---|---|---|
| | Cd | Cr | Cu | Ni | Pb | Zn |
| Sludge | 38.16 | 15.67 | 6.87 | 16.24 | 23.86 | 12.91 |
| Batch Compost | 21.30 | 12.36 | 6.35 | 13.19 | 14.16 | 6.77 |
| Stockpiled Compost | 23.47 | 12.57 | 11.98 | 22.71 | 15.42 | 13.62 |
| Cured Compost | 20.59 | 16.94 | 10.60 | 36.58 | 11.20 | 9.26 |

TABLE D2   COEFFICIENTS OF VARIATION OF METALS CONCENTRATIONS IN
           SLUDGE SAMPLES (DAILY)

| DATE | NUMBER OF SAMPLES | COEFFICIENT OF VARIATION (Percent) | | | | | |
|------|------|------|------|------|------|------|------|
| | | Cd | Cr | Cu | Ni | Pb | Zn |
| 01/21/88 | 9 | 4.64 | 3.05 | 2.83 | 4.08 | 9.28 | 5.27 |
| 01/22 | 4 | 1.99 | 1.19 | 2.65 | 1.35 | 12.20 | 2.96 |
| 01/25 | 4 | 2.72 | 3.06 | 3.38 | 3.22 | 5.07 | 2.43 |
| 01/27 | 4 | 2.15 | 3.36 | 3.24 | 1.94 | 9.13 | 2.14 |
| 01/28 | 3 | 2.27 | 5.43 | 2.59 | 2.42 | 5.26 | 3.78 |
| 01/29 | 3 | 1.39 | 2.73 | 1.53 | 1.25 | 19.58 | 12.32 |
| 02/01 | 4 | 2.04 | 9.75 | 3.51 | 3.61 | 12.46 | 4.63 |
| 02/09 | 4 | 2.55 | 5.86 | 3.95 | 1.56 | 8.57 | 48.02 |
| 02/10 | 4 | 0.00 | 4.49 | 4.08 | 4.36 | 6.92 | 6.49 |
| 02/11 | 4 | 2.88 | 5.31 | 2.75 | 1.36 | 3.72 | 4.14 |
| 02/19 | 3 | 2.11 | 2.02 | 1.24 | 2.97 | 6.81 | 3.13 |
| 02/23 | 4 | 7.50 | 3.87 | 1.12 | 1.60 | 3.51 | 1.90 |
| 02/24 | 4 | 3.39 | 3.44 | 1.91 | 1.72 | 3.69 | 2.03 |
| 03/01 | 3 | 5.59 | 3.32 | 2.18 | 1.07 | 8.01 | 3.20 |
| 03/02 | 3 | 2.09 | 0.00 | 1.72 | 0.57 | 8.28 | 0.68 |
| 03/03 | 4 | 33.04 | 4.87 | 3.40 | 3.50 | 6.61 | 4.34 |
| 03/04 | 3 | 4.38 | 2.04 | 1.01 | 1.84 | 4.42 | 3.12 |
| 03/07 | 4 | 4.12 | 3.31 | 2.27 | 1.33 | 5.82 | 2.48 |
| 03/08 | 4 | 4.03 | 7.12 | 0.26 | 4.89 | 9.00 | 12.34 |
| 03/09 | 3 | 2.55 | 0.73 | 2.70 | 1.85 | 3.34 | 2.70 |
| 03/10 | 4 | 27.01 | 2.96 | 2.11 | 1.51 | 4.72 | 2.84 |
| 03/18 | 3 | 3.46 | 12.04 | 3.04 | 3.85 | 4.69 | 8.15 |
| 03/21 | 3 | 3.27 | 5.64 | 4.76 | 2.36 | 4.90 | 2.51 |
| 03/22 | 3 | 3.33 | 3.19 | 5.03 | 5.05 | 4.90 | 4.05 |
| 03/23 | 3 | 3.53 | 7.02 | 2.65 | 2.92 | 7.98 | 3.73 |
| 03/24 | 3 | 0.00 | 3.09 | 0.43 | 0.93 | 8.81 | 5.13 |
| 03/25 | 3 | 3.33 | 1.43 | 3.88 | 3.57 | 1.06 | 5.91 |
| 03/31 | 3 | 14.52 | 1.54 | 2.20 | 0.59 | 8.25 | 1.74 |
| 04/01 | 4 | 6.45 | 3.39 | 1.20 | 0.77 | 21.23 | 4.00 |
| 04/04 | 4 | 3.77 | 0.67 | 1.50 | 1.41 | 5.44 | 1.90 |
| 04/11 | 3 | 0.00 | 2.47 | 2.30 | 1.67 | 21.81 | 2.80 |
| 04/12 | 4 | 0.00 | 5.91 | 3.70 | 1.78 | 8.66 | 7.75 |
| 04/13 | 4 | 3.28 | 6.95 | 2.79 | 5.19 | 7.32 | 5.79 |
| 04/19 | 4 | 3.08 | 5.10 | 1.49 | 7.20 | 8.56 | 3.78 |
| 04/20 | 2 | 4.88 | 0.00 | 1.75 | 2.11 | 17.83 | 6.17 |
| 04/21 | 2 | 4.88 | 4.45 | 4.47 | 3.78 | 1.37 | 6.29 |
| 04/22 | 3 | 9.17 | 3.27 | 6.44 | 7.99 | 7.81 | 11.01 |
| 04/25 | 4 | 6.42 | 4.59 | 3.76 | 12.87 | 24.03 | 9.29 |
| 05/03 | 4 | 7.38 | 14.47 | 2.24 | 3.33 | 5.22 | 3.39 |
| 05/04 | 4 | 10.95 | 5.17 | 3.04 | 1.25 | 7.79 | 4.82 |
| 05/05 | 4 | 6.70 | 4.62 | 8.23 | 2.17 | 1.72 | 3.27 |
| 05/11 | 4 | 28.06 | 8.81 | 3.88 | 5.10 | 2.77 | 2.23 |
| 05/12 | 3 | 16.87 | 28.33 | 0.24 | 0.75 | 11.07 | 2.05 |

TABLE D2   COEFFICIENTS OF VARIATION OF METALS CONCENTRATIONS IN
          SLUDGE SAMPLES (DAILY)      (continued)

| DATE | NUMBER OF SAMPLES | COEFFICIENT OF VARIATION (Percent) | | | | | |
|------|-------------------|------|------|------|------|------|------|
| | | Cd | Cr | Cu | Ni | Pb | Zn |
| 05/13 | 3 | 33.68 | 39.40 | 4.93 | 3.06 | 11.92 | 4.08 |
| 05/16 | 4 | 9.87 | 4.60 | 3.53 | 2.28 | 7.30 | 1.56 |
| 05/20 | 4 | 5.92 | 6.41 | 2.63 | 2.56 | 4.05 | 3.45 |
| 05/23 | 3 | 38.98 | 62.75 | 3.54 | 2.28 | 14.03 | 1.53 |
| 05/24 | 4 | 2.46 | 12.37 | 2.49 | 3.96 | 6.66 | 5.17 |
| median | | 4.03 | 3.87 | 2.63 | 2.36 | 7.30 | 3.73 |

TABLE D3  COEFFICIENTS OF VARIATION OF METALS CONCENTRATIONS IN STORED COMPOST SAMPLES (DAILY)

| DATE | SAMPLE TYPE (1) | NUMBER OF SAMPLES | COEFFICIENT OF VARIATION (Percent) | | | | | |
| | | | Cd | Cr | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|
| 03/01/88 | CP | 2 | 7.29 | 1.41 | 4.74 | 3.14 | 5.39 | 2.69 |
| 03/17 | CP | 2 | 7.86 | 17.52 | 3.36 | 5.51 | 4.88 | 0.73 |
| | SP | 3 | 19.32 | 13.74 | 4.92 | 4.92 | 11.22 | 15.53 |
| 04/12 | CP | 3 | 3.11 | 7.56 | 4.35 | 5.98 | 2.04 | 0.42 |
| | SP | 3 | 6.93 | 6.93 | 6.94 | 11.01 | 9.17 | 7.66 |
| 05/03 | CP | 3 | 2.46 | 1.09 | 4.14 | 3.34 | 2.53 | 2.95 |
| | SP | 3 | 12.73 | 2.73 | 26.55 | 31.90 | 19.62 | 29.09 |
| 05/23 | CP | 3 | 6.10 | 8.03 | 4.21 | 1.21 | 5.75 | 2.27 |
| | SP | 3 | 1.57 | 2.81 | 2.30 | 2.15 | 2.19 | 1.43 |
| 06/21 | CP | 3 | 28.18 | 19.73 | 13.41 | 12.63 | 19.06 | 25.52 |
| | SP | 3 | 24.96 | 9.85 | 9.18 | 7.31 | 12.39 | 9.12 |

(1) CP  Curing pile
    SP  Stockpiled

TABLE D4   COEFFICIENTS OF VARIATION OF METALS CONCENTRATIONS IN
SLUDGE AND BATCH COMPOST SAMPLES (BATCH)

| BATCH | SAMPLE TYPE (1) | Cd | Cr | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|
| A | S | 6.83 | 12.66 | 7.94 | 22.30 | 9.11 | 4.17 |
|   | C | 6.30 | 5.65 | 3.85 | 4.36 | 9.11 | 5.91 |
| B | S | 6.47 | 5.84 | 3.74 | 7.11 | 17.32 | 6.74 |
|   | C | 12.37 | 10.47 | 6.71 | 4.86 | 12.32 | 7.95 |
| C | S | 2.63 | 6.87 | 6.32 | 2.85 | 6.83 | 32.51 |
|   | C | 14.29 | 9.79 | 6.16 | 5.80 | 9.57 | 4.94 |
| D | S | 6.42 | 3.67 | 2.08 | 9.71 | 4.55 | 2.54 |
|   | C | -- | -- | -- | -- | -- | -- |
| E | S | 20.33 | 5.56 | 2.49 | 1.97 | 6.42 | 3.45 |
|   | C | -- | -- | -- | -- | -- | -- |
| F | S | 13.15 | 4.92 | 1.92 | 4.36 | 5.71 | 6.19 |
|   | C | 16.78 | 12.96 | 11.98 | 6.44 | 10.16 | 7.69 |
| G | S | 4.48 | 6.38 | 3.72 | 4.79 | 5.67 | 5.00 |
|   | C | 3.71 | 2.25 | 3.40 | 11.59 | 4.77 | 5.26 |
| H | S | 14.26 | 5.84 | 2.24 | 2.25 | 12.99 | 4.05 |
|   | C | 8.37 | 5.69 | 5.08 | 2.78 | 9.44 | 6.77 |
| I | S | 2.03 | 6.70 | 4.18 | 4.08 | 15.64 | 6.86 |
|   | C | 5.73 | 2.23 | 2.14 | 1.77 | 4.16 | 5.27 |
| J | S | 9.90 | 3.71 | 3.78 | 8.74 | 15.53 | 7.68 |
|   | C | 6.81 | 8.09 | 2.14 | 4.94 | 3.49 | 3.61 |
| K | S | 22.93 | 10.48 | 5.45 | 5.66 | 10.65 | 4.63 |
|   | C | 4.08 | 6.08 | 1.92 | 2.72 | 6.16 | 4.10 |
| L | S | 25.27 | 26.52 | 6.03 | 5.10 | 12.32 | 4.43 |
|   | C | 5.42 | 6.43 | 3.16 | 3.87 | 5.87 | 3.42 |
| M | S | 23.20 | 30.87 | 6.16 | 6.83 | 9.86 | 4.73 |
|   | C | 4.57 | 3.99 | 3.31 | 3.50 | 3.40 | 2.94 |
| median | S | 9.90 | 6.38 | 4.18 | 5.10 | 9.86 | 4.73 |
|   | C | 6.30 | 6.08 | 3.40 | 4.36 | 6.16 | 5.26 |

(1) S sludge
     C batch compost

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TABLE D5    COEFFICIENTS OF VARIATION OF AVERAGE METALS
CONCENTRATIONS (ALL BATCHES)

| SAMPLE | COEFFICIENT OF VARIATION (Percent) | | | | | |
|--------|------|-------|------|-------|-------|------|
| TYPE | Cd | Cr | Cu | Ni | Pb | Zn |
| SLUDGE | 36.89 | 10.93 | 4.60 | 14.02 | 22.50 | 8.99 |
| BATCH COMPOST | 19.24 | 10.24 | 4.02 | 11.85 | 12.63 | 4.50 |

TABLE D6    COEFFICIENTS OF VARIATION OF PERCENT CHANGE IN SLUDGE
METALS CONCENTRATIONS DURING COMPOSTING

| METAL | COEFFICIENT OF VARIATION (Percent) |
|-------|------|
| Cd | 60 |
| Cr | 72 |
| Cu | 43 |
| Ni | 89 |
| Pb | 91 |
| Zn | 59 |