RECLAMATION OF SULPHIDE TAILINGS USING MUNICIPAL SOLID WASTE COMPOST: LITERATURE REVIEW AND RECOMMENDATIONS

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RECLAMATION OF SULPHIDE TAILINGS
USING MUNICIPAL SOLID WASTE COMPOST:
LTTERATURE REVIEW AND RECOMMENDATIONS

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EXECUTIVE SUMMARY

Falconbridge Limited requested that the Centre in Mining and Mineral Exploration Research at Laurentian University conduct a literature review and make recommendations on the use of municipal compost in the reclamation of sulphide tailings. The extent and continuing burden of acid mine drainage (AMD) from sulphide tailings has prompted the federal and provincial governments, and the mining industry to look for permanent solutions. This report describes the basis of the AMD problem and the major solutions that have been proposed for tailings abandonment. One promising approach is the creation of an oxygen barrier on tailings that would prevent penetration of atmospheric oxygen, which is the main agent of tailings oxidation and AMD production.

The establishment of artificial wetlands on tailings is being researched and applied at some sites to form an oxygen barrier and create a chemical reducing regime in the tailings. However, many tailings sites are not amenable to flooding or the maintenance of wetlands. New forms of oxygen barriers are under development that wilt maintain a layer of water saturated material on top of the tailings and greatly supress oxygen diffusion. The cover layer could consist of fine, silt-like material, but this material is very expensive or not locally obtainable in the tailings areas of the north. Municipal solid waste (MSW) compost is proposed as a material which could be used as an oxygen barrier cover, for tailings. The compost layer would function as both a physical barrier and as an oxygen-consuming layer that would permanently prevent sulphide oxidation and the resultant AMD.

The vast areas of sulphide tailings in Canada would require a great amount of MSW compost for such reclamation. In 1991, Ontario municipalities were told by the provincial government to divert 50% of the solid waste stream from landfills and incineration by the year 2000. An important component of meeting this goal is the recycling of organic waste by making compost. The tailings cover approach could utilize all the MSW compost that could produced in Ontario for many decades. This application appears to be a “win-win” situation for both the mining industry and the municipalities, providing it is technically feasible, environmentally safe and socially acceptable,

Study Objectives

This literature review addresses the following objectives:

1) Review what is already understood about remediation of acidic mine tailings to avoid the problem of acid mine drainage,

2) Determine what is known about the characteristics of MSW compost and other types of organic matter, and how these wastes could be used in tailings reclamation,

3) Examine environmental regulations and socioeconomic concerns about the use of MSW compost, sewage sludge and other large volume sources of organic matter,

4) Examine the availability and costs of using MSW compost,

5) Recommend experimental studies to address unresolved technical questions about MSW compost and other organic materials as oxygen barriers on tailings.

Conclusions

A literature review of what is known about the physical and chemical characteristics of MSW compost, and other organic materials, revealed that a compost layer on tailings could be beneficial in five ways:

(1) *Physical oxygen barrier* - the compost would be saturated with water over at least part of its depth so that the limiting factor in oxygen diffusion would be the diffusivity of oxygen in water;

(2) *Oxygen-consuming barrier* - the continued decomposition of compost creates a large biological oxygen demand that acts as a sink for diffusion of atmospheric oxygen or dissolved oxygen;

(3) *Chemical inhibition* - compounds and decomposition products in the MSW compost that leach into the tailings inhibit the growth and metabolism of sulphate-producing bacteria;

(4) *Chemical amelioration* - organic constituents in the MSW compost can cause the reductive dissolution of ferric oxides and prevent indirect ferric sulphide oxidation and acid generation;

(5) *Reduced wafer infiltration* - reduced hydraulic conductivity of compacted compost may prevent infiltration of precipitation, thus decreasing tailings groundwater flow.

Three compost cover layer models are proposed to produce and maintain these functions. Two models consist of a layer of compost (of undetermined depth), which is compacted by an overburden layer of sand and gravel. In one model the bottom of the compost layer is separated from the tailings by another coarse layer to hydraulically isolate it from the tailings. In one model, compost is ploughed into the upper layer of tailings before the compacted compost is placed, so that there is chemical contact between the compost and the oxidized portion of the tailings. The main purpose of the overburden layer is to keep the compost layer permanently compacted so that air-filled pore space is minimized and incoming precipitation can produce a high degree of saturation. The overburden will also be a protective layer against erosion, evaporation and runoff which could destroy the compost layer as an oxygen barrier. The third and most inexpensive compost model consists of a deep layer of compost placed directly on the tailings.

Experimental investigations in the laboratory are required to assess whether the compost cover layer models will function as expected, in the field. Other waste materials can also be incorporated into the compost cover layer to investigate how they alter its physical and chemical properties. Analyses are also required of the leachates that come out of the compost cover layers and tailings, since MSW compost may release heavy metals, organic chemicals and pathogens into the environment. Ontario has released strict guidelines for compost quality which necessitate excellent source separation and production control in order to meet the specifications for “unrestricted use” compost.

The risks of contaminants are largely a function of the quality of the feedstocks and the optimization of the composting process. For MSW compost, separation of organic waste from non-biodegradable garbage and hazardous chemicals is essential in producing uncontaminated, high-quality compost. Sewage sludge compost may also become a high-quality material if pathogens are killed and if the wastewater stream is uncontaminated by industrial effluents. However, immature, uncured composts offer advantages for use in tailings reclamation because of their high oxygen-consuming demand and the presence of a wide variety of organic compounds that could function in chemical amelioration of AMD. Immature compost could also be diverted much earlier in the composting process and be much cheaper for a municipality to produce.

The quality of leachates from mature and immature MSW compost and other organic waste components used on tailings will require careful experimental examination to ensure public health and environmental safety. Early and genuine involvement by the community is essential to the acceptance of any tailings reclamation plan involving MSW compost or other organic wastes.

Other waste materials offer some or all the benefits of MSW compost as an oxygen barrier. Forest industry and paper mill wastes are plentiful and a nuisance in many of the areas of Canada where tailings are located. Peat is a common and abundant natural' material in bogs throughout the north and may be useful for tailings covers, if it can be managed as a renewable resource. Tailings leachates will have to be tested for harmful compounds from these wastes, as well as for any beneficial effects on AMD.

MSW compost or other organic wastes will be useful for the mining industry only if they provide a permanent, socially-acceptable and cost-effective solution to tailings abandonment. Even if the municipalities provide MSW compost at no charge or with subsidization, transportation costs from the major sources in the south to tailings sites in the north may be prohibitive for a mining company. Ontario government policy and regulations that currently prevent the export of waste from a municipality should be examined with respect to low-grade compost use for tailings reclamation.

Recommendations

1. Laboratory work using instrumented leaching columns should be conducted to test the physical aspects and optimization of the compost cover layer models.

2. Laboratory analyses of leachate composition from unsaturated and saturated compost layers, containing compost of various degrees of maturity, are required to establish environmental risk.

3. Laboratory studies of chemical processes within tailings under the optimal cover layer design will confirm whether reducing conditions are present and chemical amelioration is occurring.

4. Field lysimeter studies of the optimal compost cover layer design, as determined by laboratory experiments, should be conducted at the Nickel Rim tailings site.

5. Discussions should be initiated by Falconbridge Ltd. with provincial government ministries, municipal government and the community concerning the use of MSW compost in tailings reclamation.

SOMMAIRE

Falconbridge a demandé que le Centre de recherche en exploitation minière et exploration minérale de l'Université Laurentienne procède à une étude de la documentation scientifique et fasse des recommandations sur l'utilisation de compost municipal pour la réhabilitation des résidus sulfurés. Le volume et le fardeau que représentent les eaux de drainage minier acide (DMA) s'écoulant des résidus sulfurés ont incité les gouvernements fédéral et provinciaux, et l'industrie minière, à chercher des solutions permanentes. Le présent rapport décrit le fondement du problème du DMA et les grandes solutions qui ont été proposées pour l'abandon des parcs à résidus. Une approche prometteuse consiste à recouvrir les résidus d'une barrière qui empêcherait la pénétration de l'oxygène atmosphérique, principal agent d'oxydation des résidus et de production du DMA.

La mise en place de marécages artificielles sur les résidus est examinée et appliquée sur certains emplacements pour former une barrière efficace à l'oxygène et établir un régime de réduction chimique dans les résidus. Toutefois, de nombreux parcs à résidus sont difficiles à inonder ou à recouvrir de marécages. De nouvelles formes de barrières contre l'oxygène sont en voie d'élaboration pour maintenir une couche saturée par-dessus les résidus et diminuer grandement la diffusion de l'oxygène. La couche serait composée d'un matériau limoneux fin, mais ce matériau est très coûteux, voire introuvable, dans les zones du nord ou se trouve les résidus. Il est proposé d'utiliser du compost de déchets solides municipaux @SM) autant comme barrière physique que comme couche qui consomme l'oxygène et qui empêcherait en permanence l'oxydation des sulfures et la formation du DMA.

La réhabilitation des vastes étendues de résidus sulfurés au Canada exigerait des quantités considérables de compost de DSM. En 1991, les municipalités de l'Ontario ont été avisées par le gouvernement provincial de mettre de côté 50%, d'ici à l'an 2000, des déchets solides destinés aux dépotoirs et aux incinérateurs. Un volet important de cet objectif est le recyclage des déchets organiques par compostage. Cette approche, consistant à recouvrir les résidus d'une couverture de compost permettrait d'utiliser tout le compost de DSM produit par l'Ontario pendant des décennies. Cette application semble doublement prometteuse autant pour l'industrie que pour les municipalités, à condition qu'elle soit techniquement faisable, sûre pour l'environnement et socialement acceptable.

Objectifs de l'étude

La présente étude de la documentation vise les objectifs suivants:

(1) Examiner l'état des connaissances actuelles sur la réhabilitation des résidus miniers acides pour éviter le problème du DMA

(2) Déterminer ce qui est connu au sujet des caractéristiques du compost de DSM et des autres types de matières organiques, et comment ces déchets pourraient être utilisés pour la réhabilitation des résidus

(3) Examiner la réglementation sur l'environnement et les préoccupations socioéconomiques liés à l'utilisation du compost de DSM, des boues d'usines d'épuration et des autres sources abondantes de matière organique

(4) Examiner la disponibilité et les coûts d'utilisation du compost de DSM

(5) Recommander des études expérimentales sur les questions techniques irrésolues concernant l'utilisation du compost de DSM et d'autres matières organiques comme barrières contre l'oxygène sur les résidus.

Conclusions

Une étude de la documentation scientifiques sur les caractéristiques physiques et chimiques du compost de DSM et d'autres matières organiques a révélé que l'épandage d'une couche de compost sur les résidus serait avantageux pour cinq raisons:

(1) *Barrière physique contre l'oxygène* - le compost serait saturé d'eau sur une partie de son épaisseur, de sorte que le facteur limitant la diffusion de l'oxygène serait la diffusivité de l'oxygène dans l'eau;

(2) Barrière qui consomme l'oxygène - la décomposition continue du compost crée une forte demande biologique en oxygène qui agit comme un puits dans la diffusion de l'oxygène atmosphérique ou de l'oxygène dissous;

(3) Inhibition chimique - les composés et les produits de décomposition dans le compost de DSM qui sont lixiviés dans les résidus ralentissent la croissance et le métabolisme des bactéries productrices de sulfates;

(4) Amélioration chimique - les constituants organiques dans le compost de DSM peuvent dissoudre par réduction les oxydes ferriques, et empêcher l'oxydation indirecte des sulfures ferriques et la production d'acide;

(5) Infiltration d'eau réduite - la conductivité hydraulique réduite du compost tassé pourrait empêcher l'infiltration des précipitations, diminuant ainsi l'écoulement d'eau souterraine dans les résidus.

Trois modèles de couvertures de compost sont proposés pour réaliser et maintenir ces fonctions. Deux modèles consistent en une couche de compost (d'épaisseur indéterminée) qui est tassée par une couche sus-jacente de sable et de gravier. Dans un des modèles, la base de la couche de compost est séparée des résidus par une autre couche grossière qui l'isole hydrauliquement des résidus, Dans un autre modèle, le compost est mélangé à la couche supérieure des résidus avant que du compost soit tassée en place, établissant ainsi un contact chimique entre le compost et la partie oxydée des résidus. Le but premier de la couche de couverture est de maintenir un contact permanent avec la couche de compost, de sorte qu'il y ait le moins d'air interstitiel possible et que les précipitations incidentes puissent se traduire par une saturation élevée. La couche de couverture protège aussi contre l'érosion, l'évaporation et le ruissellement qui pourraient détruire la couche de compost agissant comme barrière contre l'oxygène. Le troisième modèle, le moins coûteux, consiste à déposer une couche épaisse de compost directement sur les résidus.

Des recherches expérimentales en laboratoire s'imposent pour évaluer si les modèles de couvertures de compost produiront les résultats escomptés sur le terrain. D'autres types de déchets peuvent aussi être incorporés dans la couche de compost, ce qui permettrait d'étudier comment ils altèrent ses propriétés physiques et chimiques. Il faudrait aussi analyser les lixiviats qui s'écoulent des couches de compost et des résidus, car le compost de DSM pourrait libérer des métaux lourds, des composés organiques et des agents pathogènes dans l'environnement. L'Ontario a adopté des normes rigoureuses de qualité des composts qui doivent subir une séparation à la source et un contrôle de la production poussés pour être désignés compost “d'utilisation non restreinte”.

Les risques de contamination dépendent grandement de la qualité des matières premières et de l'optimisation du procédé de compostage. Pour produire un compost de DSM de grande qualité qui n'est pas contaminé, il faut séparer les déchets organiques des ordures non biodégradables et des produits chimiques dangereux. Le compost de boues d'usines d'épuration peut aussi devenir un produit de grande qualité si les agents pathogènes sont éliminés et si les eaux usées ne sont pas contaminées par des effluents industriels. Toutefois, les composts jeunes offrent des avantages pour la neutralisation des résidus à cause de leur forte consommation d'oxygène et de la présence de nombreux composés organiques qui pourraient contribuer à améliorer la chimie du DMA. Les composts jeunes pourraient aussi être utilisés plus tôt dans le compostage et leur production cotîterait moins cher aux municipalités.

Pour s'assurer de la qualité des lixiviats de composts de DSM jeunes et mûrs et d'autres constituants de déchets organiques utilisés sur des résidus, il faudra en faire un examen expérimental minutieux garantissant que leur usage est sain pour la santé publique et sûr pour l'environnement. Il faut que l'engagement sincère de la population soit pris avant qu'un plan de neutralisation des résidus faisant intervenir du compost de DSM ou d'autres déchets organiques soit acceptable.

D'autres types de déchets offrent certains ou tous les avantages du compost de DSM comme barrière contre l'oxygène. Les déchets de l'industrie forestière et des usines de papier sont abondants et nuisibles dans nombre de régions du Canada où l'on trouve des résidus. La tourbe est un matériau courant et abondant dans toutes les tourbières du nord et conviendrait comme couverture pour les parcs à résidus, si elle peut être gérée comme une ressource renouvelable. Les constituants dangereux de ces résidus, contenus dans les lixiviats, devront être analysés, et leurs effets bénéfiques sur le DMA, devront être évalués.

Le compost de DSM ou les autres déchets organiques ne seront utiles à l'industrie minière uniquement s'ils constituent une solution permanente, socialement acceptable et rentable au problème de réhabilitation des résidus. Même si les municipalités fournissent le compost de DSM sans frais ou par voie subventionnée, les coûts de transport depuis les principales sources dans le sud jusqu'aux parcs à résidus dans le nord pourraient être prohibitifs pour une société minière. La politique et la réglementation du gouvernement ontarien qui interdisent actuellement l'exportation de déchets par une municipalité devraient être examinées en termes d'utilisation de composts de qualité médiocre pour réhabiliter les résidus.

Recommandations

1. Des travaux de laboratoire à l'aide de colonnes de lixiviation instrumentées devraient être effectués pour étudier les caractéristiques physiques et l'optimisation des modèles de couvertures de compost.

2. Des analyses en laboratoire de la composition des lixiviats provenant de couches saturées et non saturées, contenant du compost de maturité variable, s'imposent pour déterminer le risque pour l'environnement.

3. Des études en laboratoire des phénoménes chimiques qui ont cours dans les résidus suivant le modèle de couche de couverture optimal confirmeront s'il y a réduction et amélioration chimique.

4. Des études lysimétriques du modèle de couche de compost optimal, tel qu'établi par des expériences en laboratoire, devraient être menées au parc à résidus Nickel Rim.

5. Des discussions sur l'utilisation de compost de DSM pour neutraliser le DMA devraient être amorçées par Falconbridge avec les ministères provinciaux, les gouvernements municipaux et la population.

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Dr. Lewis Molot, of the Faculty of Environmental Studies at York University, provided access to his recent study of the viability of using municipal compost for the treatment of acid mine drainage. A conversation with Dr. Molot also contributed key ideas to the solutions proposed in this study.

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1. INTRODUCTION

1.1 Overview of the Acid Mine Drainage Problem

Tailings are the waste product left over after mineral ores are milled and the valuable minerals are extracted. Tailings are stored in large impoundments on mine company lands and are usually in an untreated state. The extent of tailings deposits in Canada is vast and ground cover estimates are in excess of 15,000 hectares - the area of a medium-size city. The mining of lower grade ores, together with the likelihood of increasing annual production, could lead to the accumulation of an equal quantity of acidic tailings and waste rock over the next twenty years (Feasby et *a/.* 1991).

The tailings often contain 90% of the ore's sulphide minerals, particularly the iron sulphides pyrite and pyrrhotite, which are potential sources of acidity and heavy metals pollution (Feasby *et al.,* 1991). If acid drainage is not collected and treated, the drainage could contaminate groundwater and water courses. At active mine sites (and some inactive sites), mining companies operate comprehensive systems to collect and treat effluents and seepage from all sources. These facilities, when well operated and maintained, are sufficient to prevent downstream impacts to the environment. However, acid generation may persist for hundreds of years following mine closure and the sludges from treatment are themselves a waste product of considerable quantity. The operation of treatment plants for very iong periods of time is clearly not desirable and runs counter to the principles and goals of sustainable development (Feasby *et al.* 1991).

In the last two decades, the greatly improved understanding of tailings oxidation processes and the increasing demands by society for reclamation of industrially-damaged mining lands have led to an acceleration of study and innovation in environmental rehabilitation. For the mining industry, environmental liabilities imposed by new legislation and regulations have added a major cost component and risk to their business. Great advances have been made in the avoidance and control of air pollution, but the requirement for detailed plans for mine closure has put a new urgency on permanent solutions for the problems of tailings reclamation and acid mine drainage.

<u>Principles of Acid Generation</u>

Sulphide oxidation in reactive tailings affects other geochemical processes, such as acidification, and the subsequent dissolution of other tailings constituents, including metals (Stumm & Morgan, 1981). The oxidation process, in the absence of appreciable buffer materials, releases acidity and metals into water draining from tailings impoundments. An understanding of the sulphide oxidation process and the controlling mechanisms is therefore a key requirement for developing measures to prevent the formation of acid waters or to minimize their adverse environmental impact (Yanful *et al.* 1990).

The two sulphides of primary concern in reactive tailings are pyrite (FeS_2) and pyrrhotite ($Fe_{1-x}S$, where x values are between 0 and 0.2). Since the chemical compositions of these minerals are similar, oxidation and the resulting acidification processes are also similar for both minerals. Pyrite is the often the dominant mineral and is used here as the example in the chemical reactions of tailings oxidation, although pyrrhotite oxidizes more rapidly.

The oxidation of pyrite in the presence of oxygen and water can be represented by the following equation (Stumm & Morgan 1981):

$$2FeS_2\ (s)\ +\ 70,\ +\ 2H_2O\ \text{--->}\ 2Fe^{+2}\ +\ 4SO_4^{2-}\ +\ 4H^+ \qquad [1]$$

The dissolved Fe^{2+}, SO_4^{2-} and H^+ represent an increase in total dissolved solids and acidity of the water. For a low-pH system (i.e. pH 1.5 to 3.5) in which oxygen is readily available, subsequent oxidation of ferrous ion, Fe^{2+}, will occur producing ferric iron, Fe^{3+}, as follows:

$$4Fe^{2+}\ +\ 0,\ +\ 4H^+\ \text{<--->}\ 4Fe^{3+}\ +\ 2H_2O \qquad [2]$$

The oxidation of ferrous iron is the rate-limiting step with a half-time of about 1000 days (Stumm & Morgan 1981). Ferrous oxidation to ferric iron in the pH range 1.5 to 3.5 (Equation 2) is sometimes catalyzed by the autotrophic iron bacterium, *Thiobacillus ferrooxidans,* which may increase the reaction rate by a factor of 10^6 over the abiotic process (Singer & Stumm, 1970). The dependence of *T. ferrooxidans* on low pH is believed to be a requirement for chemiosmotic ATP generation based on the large pH gradient from the medium across the plasma membrane into the neutral cytoplasm (Brown 1991).

The reactions in Equations (11 and (21 can be combined to yield:

$$4FeS_2\ +\ 150,\ +\ 2H_2O\ \text{--->}\ 4Fe^{3+}\ +\ 8SO_4^{2-}\ +\ 4H^+ \qquad [3]$$

The reaction in Equation [3] indicates that both the Fe^{2+} and S_2^{2-} of FeS_2 (s) can oxidize resulting in the formation of two moles of SO_4^{2-} and one mole of H^+ for each mole of FeS_2 oxidized. Ferric iron, Fe^{3+}, released as in either Equation [2] or [3], will further oxidize pyrite, thereby generating additional dissolved ferrous iron and acidity, as shown by:

$$14Fe^{3+}\ +\ FeS_2\ (s)\ +\ 8H_2O\ \text{--->}\ 15Fe^{2+}\ +\ 2SO_4^{2-}\ +\ 16H^+ \qquad [4]$$

In comparison with Equation [1], Equation [4] shows that 16 moles of H^+ are generated for each mole of pyrite oxidized. Thus, Equation [4] underscores the important role played by dissolved ferric iron in the whole oxidation process and' the subsequent generation of acidity. The rate-limiting step is the oxidation of Fe^{2+} by oxygen (Singer & Stumm 19701, and under field conditions, the diffusion rate of oxygen to pyrite is the limiting process (Postma 1983).

At slightly higher pH values (i.e. 4 or greater), hydrolysis of Fe^{3+} will occur, resulting in the precipitation of ferric hydroxide and further generation of acidity as indicated by:

$$Fe^{3+}\ +\ 3H_2O\ \text{<--->}\ Fe(OH)_3\ (s)\ +\ 3H^+ \qquad [5]$$

The hydrolysis reaction is reversible and indicates that $Fe(OH)_3$ (s) is more stable at high pH values or decreasing concentrations of H^+. When the pH decreases, $Fe(OH)_3$ (sl becomes more soluble and Fe^{3+} more stable. Under these conditions, reaction [5] does not contribute significantly to acidification. Any Fe^{3+} from reaction [2] that does not precipitate from solution through reaction [5] may be used to oxidize additional pyrite, as in reaction [4].

The overall process of pyrite oxidation can be represented by combining Equations [3] and [5] to give:

$$4FeS_2(s) + 150, + 14H_2O \text{ ---> } 4Fe(OH)_3(s) + 8SO_4^{2-} + 16H^+ \qquad [6]$$

Thus, in an acidic environment a cyclical system develops in which'ferrous ions released from pyrite are oxidized bacterially to ferric ions, which can then further oxidize pyrite, generating more ferrous ions. This system leads to massive production of acid in the tailings pore water (Backes et *al*. 1986, Brown 1991). Stumm and Morgan (19811 presented a simplified model of the processes of pyrite oxidation (Fig. 1).

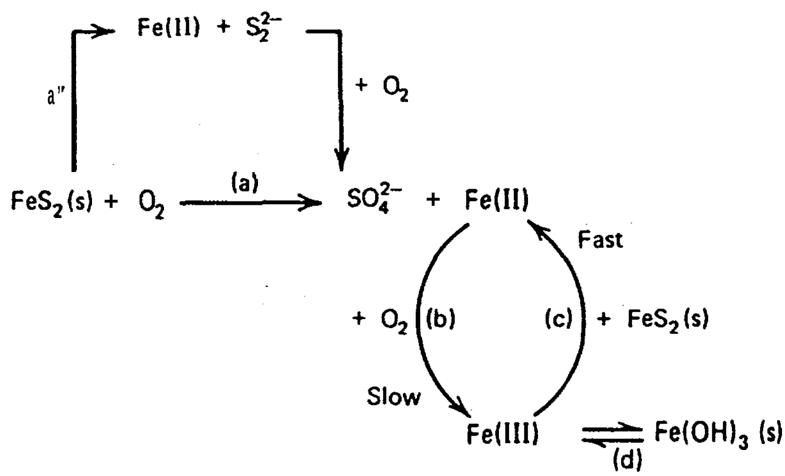

Figure 1. Simplified model of pyrite oxidation processes (from Stumm & Morgan 1981): (al Oxidation by atmospheric oxygen;, (a') dissolved then oxidized; (b) slow oxidation of ferrous iron, the rate-determining reaction which may be catalyzed by bacteria; (cl rapid reduction of ferric iron by pyrite, releasing acidity and ferrous iron; (d) precipitation of ferric hydroxide which is reversible by dissolution of solid $Fe(OH)_3$.

At a neutral pH, created for example by liming, *T. ferrooxidans* will be inactive and the dominant pathway will be reaction [7], a slow process which is limited by the rate of oxygen diffusion (Backes *et al.* 1986):

$$2FeS_2(s) + 0, + 4H^+ \text{ ---> } 2Fe^{2+} + 4S^o + 4H_2O \qquad [7]$$

However, re-acidification often occurs as the lime is neutralized or washed out of the surface layers, when *T. ferrooxidans* directly oxidizes sulphur to obtain electrons for energy, Equation (81, or catalyzes the rapid Fe^{2+} --> Fe^{3+} oxidation (Brown 1991).

$$2S^o + 30, + 2H_2O \text{ ---> } 2H_2SO_4 \qquad [8]$$

Mobilization of Metals

Metal sulphide minerals are significant solid phases in mine tailings and pollutant remobilization will be strongly dependent on the redox reactions taking place after disposal. Under oxidizing conditions solid sulphides are dissolved and trace. metals are no longer controlled by sulphide equilibria but rather by adsorption/desorption or, in limited cases, by other precipitation processes (Bourg 1988).

iron, in both its divalent and trivalent state, plays a central role in sulphide mineral degradation (Kelley & Tuovinen 1988). The products of these reactions, ferric sulphate and sulphuric acid, provide an excellent means of dissolving a variety of mineral sulphides by what is often termed the 'indirect" mechanisms of bacterial attack:

$$MS + Fe_2(SO_4)_3 \dashrightarrow MSO_4 + 2FeSO_4 + S^o \quad 191$$

where M represents a bivalent metal. The ferrous sulphates thus produced are further oxidized in microbial systems (Kelley & Tuovinen 1988).

The factors that can affect the remobilization of trace metals from solid waste materials are: lowering the pH, increasing the occurrence of natural and synthetic complexing agents, increasing salt concentrations and changing redox conditions. Chemical extraction sequences have been developed to estimate the reactivity, mobility and bioavailability of each metal species under different environmental conditions (Forstner & Kersten 1988).

Factors Controllina Oxidation

The activity and number of bacteria are determined primarily by physical factors such as moisture content, aeration and availability of electron donor substrates. *T. ferrooxidans* is regarded as an aerobic organism, but has been seen to oxidize zinc-sulphide ore in the presence of CO,. Under anaerobic conditions the bacteria couple the oxidation of inorganic sulphur to the reduction of Fe^{+3} to Fe^{2+} (Kelley & Tuovinen 1988). Equations 11 I and 121 show that if oxygen is not available, then the intermediate Fe^{3+} will not be generated and the oxidation process (Equations 3 and 4) will not occur (Yanful et *al. 1990).*

In tailings, sulphide oxidation generally occurs at shallow depths above the water table. Under moist conditions the ultimate driving force is availability of oxygen and the rate of oxygen transport into the porous material (Nicholson *et* al. 1989, Yanful *et al.* 1990). However, bacterial oxidation processes appear to be tolerant of low oxygen concentrations, as low as 5% of the saturation levels in water (Yanful *et al.* 1990). The rate at which oxygen diffuses into the tailings primarily controls the rate of acid generation.

Both the chemical and biological oxidation pathways are dependent on temperature. A 10 °C temperature increase will double to triple the chemical reaction rate with an optimal range of 28 to 40 °C for microbial reactions. Since pyrite oxidation is an exothermic process, a temperature increase is commonly found in the unsaturated layer of tailings where oxidation rates are greatest (Yanful *et al.* 1990).

Acidity also plays a key role in the activity of bacteria that catalyze the oxidation of pyrite. Another bacterial group, *Metallogenium,* has been implicated in pyrite oxidation. This bacterium is acid tolerant at the pH range of 5 to 3.5, then *T. ferrooxidans* takes over and reduces the pH below 3.5 (Yanful *et al.* 1990).

The availability of CO, may control the kinetics of bacterial population growth since biosynthesis commonly uses CO, as its carbon source for the synthesis of organic biological molecules. The optimal CO, level has been found to be 0.22% but it can be much higher in tailings with carbonate materials and may be satisfied by CO_2 dissolved in infiltrating rain water. Nutrients, such as nitrogen, phosphorus and potassium, are also required but the small concentrations seen are sufficient for bacterial growth (Yanful et al. 1990). Ferrous iron is a major source of electrons for *T. ferrooxidans* respiration and could become a limiting factor if most of it became oxidized.

I .2 Proposed Solutions for Tailings Abandonment

Beginning more than two decades ago, the mining industry, university and government researchers worldwide have conducted a great deal of research into revegetation of tailings and waste rock (Sutton & Dick 1987, Pulford 1991). Successful, economical revegetation methods have been developed and implemented at many sites (e.g. Michelutti 1974). However, after several years of good surface stabilization, the quality of drainage from these reclaimed sites has not improved significantly (e.g. Coggans et *al.* 1991) and drainage water treatment, such as lime plants or stream liming, must be operated far into the future unless other solutions are found (Feasby *et al.*, 1991). Impoundment of AMD water and the establishment of engineered wetlands have been proposed and implemented in a few cases (cf. Dave & Lim 19891. The goal is to reverse the acidification through passive biological reduction processes found in wetland sediments- (e.g. Kalin & Smith 1991). The longterm functioning and success of wetland treatment solutions is not yet known.

The search continues for tailings abandonment or perpetual-treatment solutions that are technically sound, aesthetically pleasing to the community and economically feasible. A major thrust of research has been to find ways to stop AMD production at its source by preventing oxidation of tailings sulphides. Nicholson et a*l*. (1989) suggest that action taken to ameliorate conditions of sulphide-related acidification should be focused on one or all of the three primary factors that contribute to the oxidation processes: (1) lack of pH-buffer material, (2) catalysis by *T. ferrooxidans* and (3) oxygen availability.

As was noted in the previous section on acid generation, pH is a key environmental variable affecting the rate of acid production. At neutral pH, sulphide oxidation by chemical and biological processes is greatly suppressed. However, attempts to change the pH of tailings to reduce sulphide oxidation and AMD production, for example by liming, have been very disappointing (e.g. Dave & Michelutti 1991). The addition of anti-bacterial agents to tailings has also been attempted as a means of suppressing the activity of the microbial populations responsible for much of the sulphide oxidation (e.g. Backes *et al. 1988).* Although scientifically successful in the short term, the direct bactericide approach would likely be technically unfeasible in the field and it certainly does not represent an abandonment solution.

Many new methods and technologies have been proposed or developed in recent years to address the production of AMD, either by limiting the flow of dissolved oxygen in tailings groundwater or by preventing gaseous oxygen from reaching the sulphide materials (cf. Feasby et *al.,* 1991; Haynes & Richardson 1991, Pulford 19911. The two major approaches are termed “dry barriers” and “wet barriers”.

Dry barriers include impermeable cover materials on tailings or the alteration of the tailings surface and groundwater movement, in order to stop the infiltration of water or air which carry the oxygen necessary for sulphide oxidation. Exclusion of oxygen and water from tailings by dry covers has proven to be very difficult and expensive (Dyer 1984). Impermeable barriers, such as paper mill sludge stabilized with coal ash (e.g. Broman et *al.* 1991) or plastic sheets, are still unproven in the long term and expensive to implement (Pulford 1991). Unless all water entry to the system can be eliminated, the system drainage water from oxidized tailings may ultimately reach a new steady-state, lower in flow rate but proportionally higher in concentration of acidic products (Dyer 1984). Thus, AMD treatment continues to be necessary. Additionally, if pyritic tailings have been exposed for some time, oxidation products already produced will cause AMD in any water exposed to them.

Water has often been considered the enemy in the battle to halt the formation of AMD, but water may also be used as a tool to prevent or reverse acidification (Dyer 1984). Wet barriers include the permanent flooding of tailings by raising the water table and deposition of tailings in lakes (Pelletier 1991). Artificial marshes or bogs established on top of tailings are also being actively studied as a method of reversing the acidification as well as stabilizing the tailings surface (Balins et *al.* 1991, Brown 1991, Winterhalder 1992), although this approach is in its early stages (Dave & Lim 1989). At many tailings sites these solutions are often technically impossible to set up or are prohibitively expensive to implement and maintain.

The Oxygen Barrier Concept

An approach with many possible advantages is the use of cover materials which can maintain a high enough degree of moisture saturation to form an oxygen barrier. Hammack and Watzlaf (1990) determined that the rate of pyrite oxidation with bacteria present was independent of oxygen partial pressures above 1%. Below 1 % oxygen, the reaction rate was proportional to the oxygen partial pressure. They concluded that it was unlikely a solid cover could maintain much less than 1% oxygen, so that other techniques of bacterial inhibition would also have to be employed if complete water saturation was not possible.

Nicholson et *al.* (1989, 1990) and Yanful (199 1) have proposed a wet barrier solution involving the use of a fine, non-aggregated cover material (e.g. Touchet silt) over a coarser layer (which could be the tailings). The capillary forces in the fine layer maintain near-saturated conditions as long as precipitation input exceeds evaporation moisture losses. In contrast, the coarser under-layer drains quickly at low pressure head resulting in drastically reduced hydraulic conductivity at the fine-coarse interface. Thus, the fine layer becomes hydraulically isolated from the water column tensions (i.e. suction) in the coarse layer. As long as the gravitational head in the fine layer does not exceed its capillarity (i.e. air entry value), the fine layer will tend to remain near moisture saturation and at near zero pressure head (i.e. a drip surface is created at the fine-coarse interface), regardless of the depth to the water table. Nicholson et *al.* (1990) show the contrasting drainage characteristics of non-aggregated Touchet silt, aggregated silt and the much coarser sand (Figure 2). Note that the air entry value (AEV) is the pressure at the break point of each curve.

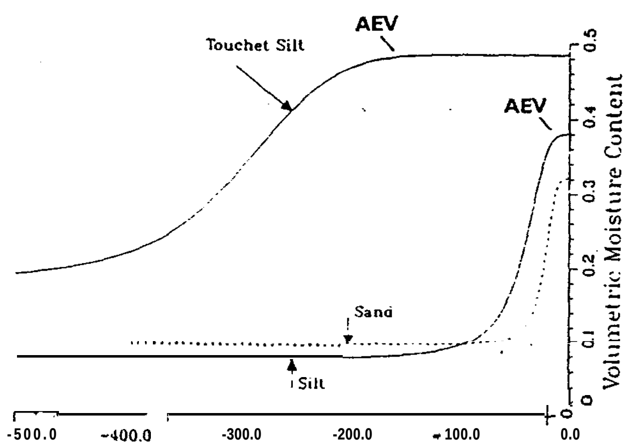

Figure 2. Drainage characteristics for non-aggregated Touchet silt, aggregated silt and sand. The air entry value (AEV) is the pressure at the point indicated (from Nicholson et al. 1990).

An oxygen barrier is created in the saturated fine layer because diffusion is the dominant mode of oxygen transport in tailings and the diffusivity of oxygen in water is 10,000 less than in air. Additionally, the absence of air-filled pore spaces prevents mass movement of air by barometric pumping, by wind shear and by volume displacement during infiltration (Nicholson et *al.,* 1989). A capillary barrier is formed in the coarse layer which prevents the upward movement of tailings water by capillary action (Spires 1975).

This elegant, physical technique of establishing a permanent oxygen barrier has some drawbacks, though. The physical requirements for the fine layer are very demanding. Nicholson et *al.* (1991) pointed out that fine material which is aggregated will have a wide distribution of pore structure that allows air entry at much lower pressure head than for non-aggregated fine material of the same particle size. They advise the use of a material such as unstructured silt with a high air-entry value that contrasts strongly with the coarse layer below. Air entry value, which is a negative pressure, decreases (i.e. becomes more negative) with decreasing grain size (Lambe & Whitman 1979).

In practice, the preparation and implementation of this oxygen barrier solution could be difficult and expensive. Clays, although fine-grained enough, have complicating factors such as workability, cracking when desiccated and lack of availability. Unfortunately, many mineral producing areas in Canada have limited quantities of fine-grained surficial deposits so that suitable silt would be very expensive to obtain. Mixtures of other materials may provide suitable characteristics for a cover but this is uninvestigated. An appropriate cover material could even be sieved or ground tailings which are low in sulphides, but the material would have to be laid down in a manner tominimize particle size segregation which would create greater porosity (Nicholson et *al.* , 1989).

Another approach to creating a permanent oxygen barrier is to have a cover layer which consumes diffusing oxygen before it reaches the tailings. The bottom sediments of natural aquatic systems function in this manner to make an anaerobic zone only centimetres below the water-sediment interface. This occurs because the rate of oxygen consumption of heterotrophic bacteria in the sediment surface exceeds the rate of oxygen diffusion from the water (Molot 1992). The rate of oxygen consumption by the bacteria is also a function of the availability of organic material as a source of carbon and nutrients for bacterial growth. Virtually all organic materials exposed to atmospheric oxygen will have microbial populations which are reducing carbon compounds aerobically.

Tailings areas, especially those situated in the Precambrian Shield, contain very little organic matter, primarily because the natural establishment of vegetation is non-existent or inhibited by the acidity and heavy metal toxicity (Winterhalder 1984). Even on artificially-revegetated tailings, the buildup of organic matter and plant roots is not sufficient to exert much biological oxygen demand (BOD) in the soil cover. As a result, revegetation of tailings has not prevented oxygen diffusion into the tailings below and the subsequent oxidation of sulphides (Coggans et *al.* 1991, Dave & Michelutti 1991).

A new approach would be to increase the BOD in the tailings cover layer using concentrated organic matter. Currently, all the organic waste materials in many communities in Canada are being sent to landfills as garbage (e.g. food and yard wastes). or require costly processing (e.g. sewage sludge) or are sitting unused as someone else's problem (e.g. paper mill sludge, sawdust and woodchips). It is an attractive idea that some of these organic material wastes could be employed as oxygen-consuming covers for tailings reclamation. This could be a solution not only for part of the mining industry's tailings problem, but urban communities would reduce the volume of municipal solid waste (MSW) going to landfills.

1.3 Overview of Municipal Solid Waste Management & Composting

Many industries have organic wastes and most have developed specific solutions to their disposal problems. Municipal solid waste, however, is largely treated as worthless material and either incinerated or buried in landfill sits. Virtually all biodegradable materials are compostable under suitable environmental conditions (Naylor *et al.* 1990). Such conditions are essentially those favourable for microbial growth: appropriate moisture content, adequate aeration and biologically-available carbon, nitrogen and other nutrient compounds.

The composition of typical municipal solid waste is shown in Figure 3. The biodegradable fraction, including paper, is approximately three-quarters of MSW. Each type of organic waste differs somewhat physically and chemically in characteristics which may be significant to how each is composted. Some wastes sources require pre-compost processing to remove unnecessary, inhibiting or harmful ingredients. Other wastes require amendments, such as bulking agents to decrease bulk density or increase porosity, to make their characteristics suitable for sustained biological oxidation.

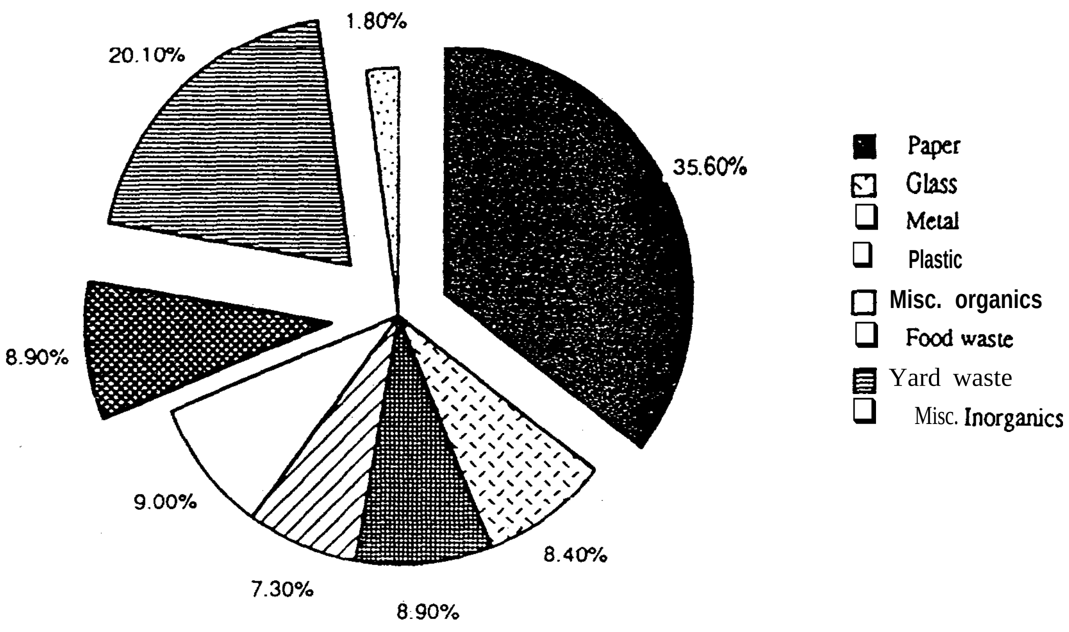

Figure 3. Composition of municipal solid waste (from Naylor et *al.* 1990).

The composting stream starts with collection of "clean" organic waste. The preferred feedstock for composting is food waste and yard waste that are free of hazardous chemicals, heavy metals and inert substances. This material is best obtained by sorting household garbage in the home into three streams (i.e. clean organics, recyclables and non-recyclables) for separate collection and handling. Hazardous household wastes represent a special pick-up stream which may or may not be recyclable (Golueke & Diaz 1989). Currently, some communities are operating a two-stream system for garbage collection by using a "blue box" collection for recyclables while organic materials and non-recyclables go to landfill. In order to retrieve the organic fraction in the two stream system, the garbage stream must be sorted and separated either mechanically or by hand into compostable organics and garbage for the landfill. Mechanical separation typically does not produce a very clean organic fraction and sorting by hand is very labour-intensive and thus too expensive.

The Comoostina Process

Once a relatively clean organic waste fraction has been obtained, there are several composting technologies from which to choose:

a) *in-vessel* employs a closed reactor in which batches of organic waste are decomposed under closely controlled, optimal conditions;

b) *aerated static pile* places batches of waste into piles that are supplied with suitable aeration and moisture for rapid decomposition;

c) *windrow*, the lowest technology approach, involves piles of waste exposed outdoors that are turned periodically to aerate and mix the decomposing layers until sufficient curing of the compost has occurred.

Often a hybrid system is employed where organic waste is given a "fast-start" decomposition for a few days in a closed vessel system then is windrowed outdoors for several weeks to mature. Open systems, although much cheaper, have problems with changing environmental conditions (e.g. winter), odours, scavengers and usually require a lot of expensive urban land. The composting process and technologies are summarized by the Ontario Ministry of the Environment Guidelines for the Production and Use of Aerobic Compost in Ontario (OMOE 1991, Appendix C; Dillon & Cal Recovery Systems 1990).

Generally speaking, composting is a slow process in which decomposable organic materials of plant or animal origin are degraded into a relatively stable, humus-like product, by the action of microorganisms. The product of the composting process is a dark, coarse, organic material, that resembles soil humus, and is light, moist and fairly odourless (Naylor *et al.* 1990). This finished compost could contain toxic compounds such as heavy metals, organic chemicals, pathogens, salts and pests if the feedstock was poor or contaminated, or if the composting process was inadequate to remove the problems. As a result, the compost would be classified as low quality rather than high quality (i.e. suitable for agriculture), and might end up unused in a landfill or treated as hazardous waste. When quality is controlled, compost is generally considered an excellent source of stabilized organic matter and is often used as a soil conditioner and low grade fertilizer (Naylor *et al.* 1990).

There is a need for a standard, quantitative method for determining the degree of decomposition or stabilization of compost (Harada & Inoko 1980). The following qualitative compost classification scheme is used in Europe (Burnham, 1991):

Level I	Raw organics or fresh compost (high biological activity)
Level II	Immature compost (highest biological activity)
Level III	First level, finished compost (medium biological activity)
Level IV	Second level, finished compost (low biological activity)
Level V	Final level, finished compost (little or no biological activity)

Some compost operations distinguish only two or three stages to compost production, often based on the technology utilized to compost. For example, the Washington Solid Waste Composting Council defines the following categories:

Stage 1	High Rate Decomposition
Stage 2	Stabilization
Stage 3	Compost Curing

Controlled microbial decomposition of organic material can occur very slowly in the absence of oxygen and this is sometimes referred to as anaerobic composting, although some authorities call this anaerobic digestion and reserve the term composting for the bio-oxidative decomposition processes.

Stage One (or Levels I and II of the aerobic process) is characterized by the rapid oxidation or degradation of low molecular weight organic constituents. Initially there is hydrolysis of carbohydrates, fats and proteins producing amino acids, monosaccharides, fatty alcohols and carbon dioxide. These are further converted into organic acids, proteins, water and more carbon dioxide. Depending on pH, C/N ratio and oxygen levels, ammonia or ammonium can also be formed, though with adequate oxygen, ammonium is oxidized to nitrate (Cave 1991).

As chemical constituents and conditions change, there is a corresponding sequence of changing bacterial populations. The heat generated by exothermic microbial processes is retained by the compost mass and raises the temperature to a moderately high level (60-70°C) which sanitizes the compost, destroying human pathogens as well as weed seeds (Vajdic 19641. Volatile organics are generally destroyed or lost, and many toxic organics are also biodegraded. Once this stage is complete, the odour potential of compost is minimized. While difficult to accurately define, this process can take from 2 days to 4 weeks, depending on the type and efficiency of the composting technology and the components of the initial waste. This material still has a strong oxygen consuming potential and can contain compounds that are toxic to plants (Garcia et al. 1990).

As stabilization advances, microbial activity gradually decreases and this corresponds to Level III or Stage 2 above. Level III can take up to 8 weeks to complete. Organic matter content may be reduced by approximately 60% by this point. Utilization of the compost at this stage for soil amendments is possible for some plant or soil types, but it can still contain compounds that are phytotoxic.

The third Stage, or Levels III to V, is often called the curing stage and its goal is to continue the humification process and produce a very stable product. This process is relatively slow, and depending on a wide variety of variables, can take up to 20 weeks. At this point, the compost reaches its most refined and marketable state. Its physical characteristics should include: dark colour, uniform particle size, a pleasant earthy odour, less than 50% moisture for easy handling and be low in visible contaminants such as glass, ceramics, metals and plastics. Its chemical characteristics should include available nutrients in the form of nitrogen, phosphorus and potassium, and low in salts, metals, pesticides, herbicides, and other hazardous organics, such as PCB's. Biologically, cured compost should be characterized by high organic matter content, absence of pathogenic organisms, absence of weed or crop seeds and be non-phytotoxic.

Total cornposting time can range from approximately 10 to 24 weeks. (Zucconi et *al.*, 1987, Burnham, 1991, Solid Waste Cornposting Council, Washington, 1991). Level V compost generally has the widest possible utilization and market potential, going primarily for horticultural and agricultural use with human food crops. Depending on the other chemical constituents of the finished compost, the soil type and type of agriculture, the application may permit the use of lower grades of compost, for example in parks, lawns or tree farms. The higher the quality of compost required and the more restricted the feedstock, the longer it takes to manufacture and the higher is its cost. Further discussion concerning compost quality will be found in Section 3 of this review.

1.4 The Opportunity for the Mining Industry

The high cost of producing quality compost, the real and perceived environmental risks of its production and use, and the lack of profitable markets for it, are a major challenges to the implementation of proven composting technologies by municipalities. The use of MSW organic matter and compost for the reclamation of industrially-disturbed lands would seem to be an attractive option to pursue since it could be a "win-win" situation for industry and many municipalities.

Molot (1992; Appendix B) did a preliminary study on the viability of using MSW compost on the control of acid mine drainage from tailings. He looked at the expected availability of compost from cities in southern Ontario such as Metropolitan Toronto and Guelph, as these communities draft plans for the cornposting of the organic fraction of their garbage. He concluded that, from the 1.0-l .1 tonne per capita annual MSW generation rate for Ontario, about 680,000 tonnes of compost could potentially be produced. This is enough compost to cover 136 hectares per year to a depth of one metre (assuming an average bulk density of 0.5 tonnes/m^3). Unfortunately, only 6% of the MSW organic wastes are generated in northern Ontario, near most of the mine lands. This fact suggests that there would not be enough volume to justify the establishment of a cornposting plant in the north and that most MSW compost would have to be imported over great distances from southern Ontario sources.

As well as MSW compost, there are many other sources of organic waste, some of which are plentiful throughout Canada: forestry product waste (bark, sawdust, woodchips), pulp and paper mill waste, food processing industry waste, municipal sewage sludge and sludge compost. Although not necessarily waste, paper products and peat are biodegradable and exist in large quantities. All of these materials are potentially useful for tailings reclamation.

Decisions are currently being made by municipalities concerning the feasibility, design and implementation of municipal cornposting systems. Customers for MSW compost, such as the mining industry, have an opportunity now to influence the building of these facilities and the drafting of public policies and government regulations concerning the handling and use of municipal wastes.

This literature review has been done as part of a multi-phase evaluation of utility of MSW compost for the long term rehabilitation and subsequent abandonment of acid-generating mine tailings. While the regulatory and policy review has focused on Ontario, the technical evaluation is generally applicable to abandonment of sulphide-rich tailings anywhere.

This literature review addresses the following objectives:

1) review what is already understood about remediation of acidic mine tailings to avoid the problem of acid mine drainage,

2) determine what is known about the characteristics of MSW compost and other types of organic matter, and how these wastes could be used in tailings reclamation,

3) examine environmental regulations and socioeconomic concerns about the use of MSW compost, sewage sludge and other large volume sources of organic matter,

4) examine the availability and costs of using MSW compost,

5) recommend experimental studies to address unresolved technical questions about MSW compost and other organic materials as oxygen barriers on tailings.

2. COMPOST AS A TAILINGS OXYGEN BARRIER

2.1 Sulphate Reduction Chemistry

The tailings cover layer models, discussed below, suggest that compost will sustain aerobic processes in the upper unsaturated layer and anaerobic processes in the lower layer, if it is in a saturated state. Reducing conditions are produced almost entirely by microbial activity (Rowell 1988). In the absence of free oxygen, a number of other substances can accept electrons and take part in microbial anaerobic respiration. Some ions containing oxygen, such as sulphate and nitrate, can accept electrons and lose oxygen (Richards 1965):

$$\underbrace{2(CH_2O)_x(NH_3)_y(H_3PO_4)_z}_{\text{organic matter}} + xSO_4^{2-} \text{ ---> } 2xHCO_3^- + xH_2S + 2yNH_3 + 2xH_3PO_4 \qquad [10a]$$

or more simply:

$$2CH_2O + SO_4^{2-} \text{ ---> } 2HCO_3^- + H_2S \qquad [10b]$$

where $2CH_2O$ represents a simple organic molecule such as acetate and H_2S is either released as a gas, ionizes to HS^- or S^{2-}, or precipitates as a polysulphide, elemental sulphur or iron sulphide, depending on the chemical environment (Hedin et *al.* 19891. Sulphate-reducing bacteria can utilize only small organic molecules (Goldhaber & Kaplan 1974).

The hydrogen sulphide produced reacts readily with iron or other metals to form insoluble sulfides such as greigite, mackinavite and pyrite (Berner 19841 and the combined reduction of sulphate and iron consumes H^+ ions and releases nutrients. Since acidity is being consumed, the pH of the medium is high in an anaerobic, reducing environment (Rowell 1988).

The important factors influencing the rate of sulphate reduction are:

1) the amount and quality of microbially-reactive organic carbon in the system,
2) the concentration of sulphate in the pore water,
3) the temperature,
4) the pressure (important only in deep sediments).

A second consequence of bacterial activity under anaerobic conditions is that the organic substrates, such as carbohydrates, are no longer fully oxidized to produce carbon dioxide and water (Rowell 1988). Instead, intermediate products are formed, such as simple fatty acids (principally acetic acid with smaller quantities of propionic, butyric, lactic, valeric, fumaric and succinic acids), hydroxy-carboxylic and polycarboxylic acids, alcohols and ketones. Some of these compounds can reduce ferric oxides, bringing iron into solution as a ferrous chelate. These compounds are further decomposed with the production of carbon dioxide, methane, nitrous oxide, ethylene, other hydrocarbons and sometimes hydrogen gas. Thus, anaerobic compost layers can contain a wide variety of inorganic arid organic compounds in reduced form.

The redox potential, E,, of a solution is a measure of the tendency of the solution to donate electrons to a reducible substance or to accept electrons from an oxidizable substance. Anaerobic conditions are represented by a low, often negative, E_h value. Figure 4 shows the E_h dependence of the sequence of microbially-mediated redox processes which are found in aqueous environments (Stumm & Morgan 1981).

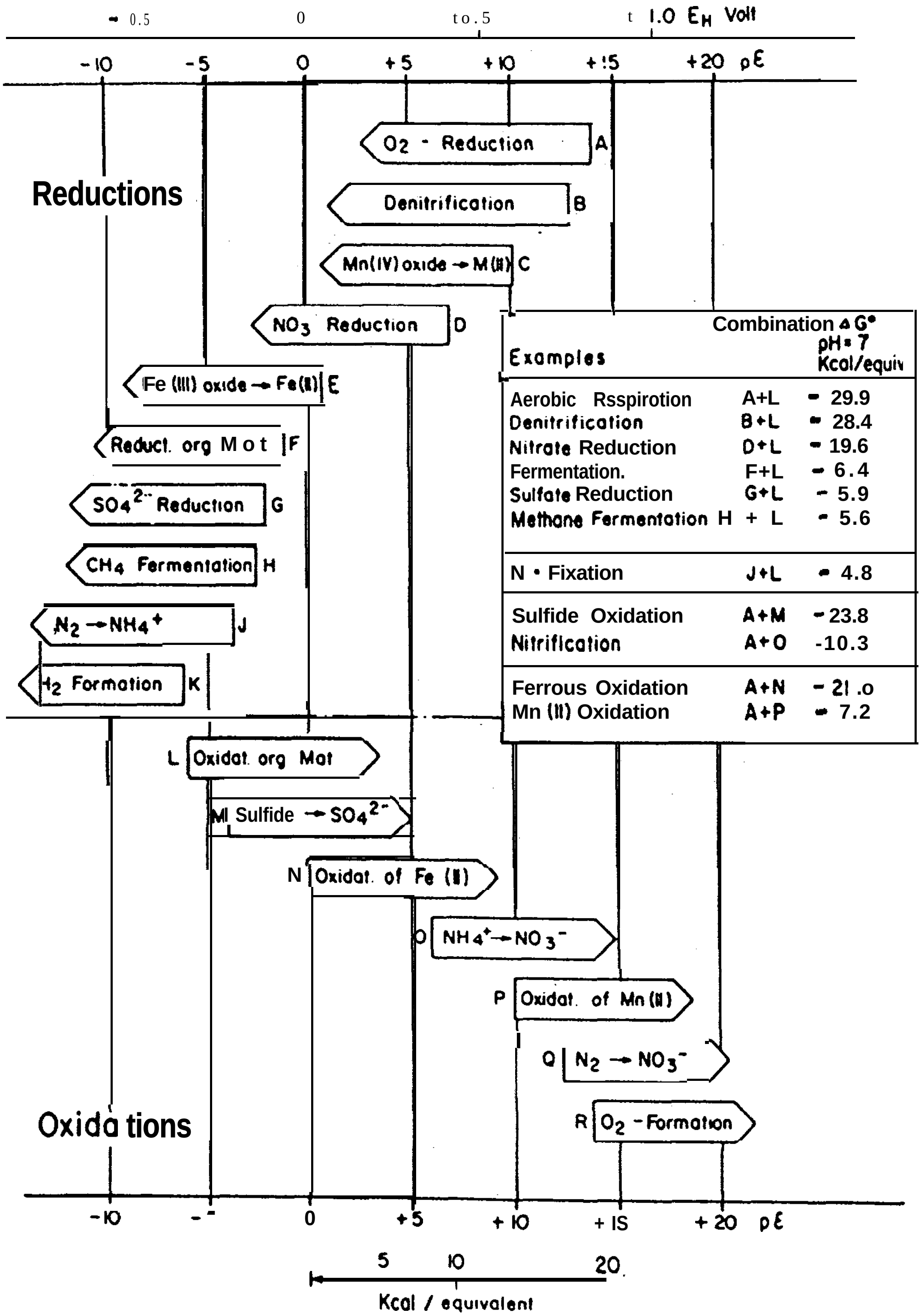

Figure 4. The sequence of microbially-mediated redox processes (Stumm & Morgan 1981)

If a solution is rich in ferric iron, then the redox potential will reflect the dominance of the Fe^{3+} reduction process until the ion is nearly all gone from solution (Rowell 1988). It is apparent in Figure 4 that sulphate reduction requires fairly strong reducing conditions (low E_h) that are present only when oxygen and other strong oxidants are absent. Ferric iron has been shown in the laboratory to inhibit sulphate reduction, probably because of the activity of iron-reducing bacteria that have an energetic advantage over the sulphate reducers (Hedin et *al.* 1989). Both sulphate and iron reduction may be energy limited in the field by lack of organic matter substrate. As a result, most AMD wetland and subaqueous treatment schemes are based on supplementing the supply of organic matter (Dave & Lim 1989, Molot 1992).

When fresh organic matter is added to an anaerobic soil solution there is a flush of microbial activity. Initially there is a fall in pH and redox potential, and a rise in CO, and the reduction products, such as organic acids. Strong reducing conditions quickly raise the concentrations of ferrous and manganous ions in the soil solution. The formation of different reduction products in waterlogged soils containing decomposable organic matter can be summarized as follows (Rowell 1988). Molecular oxygen disappears at an E_h of about 550 mV, nitrate is lost at about 400 mV, and manganous and ferrous compounds appear below 400 mV. Sulphide is formed below 0 mV and methane below -200 mV. By contrast, aerobic soils have an E_h above 600 mV.

Bacteria carrying out the decomposition release nitrogen surplus to their requirements as ammonium ions, sulphur as sulphate or hydrogen sulphide or mercaptans, and phosphorus as phosphate. These compounds will be reduced and a stable anaerobic state will be established in a few weeks. If the soil is drained and reflooded, there will be a rapid build-up in the rate of decomposition and of reducing conditions (Rowell 1988). Sulphate reduction is catalyzed almost exclusively by bacteria of the *Desulphovibrio* group which are most active at pH 6.5 to 8.5 (Rowell 1988).

In the case of compounds which have already been oxidized, such as in the upper tailings layer, the imposition of anoxic conditions can lead to the reduction of iron oxides, either by bacteria or by organic reducing compounds leached from organic matter. (This topic has been reviewed recently by Ribet et *al.* 1991; Appendix D). The result is the release of soluble Fe^{2+} ions and any trace metals adsorbed or co-precipitated with these iron oxides. The mobile Fe^{2+} can be leached out of the tailings and reoxidized by contact with oxygen resulting in the regeneration of acid:

$$4Fe^{2+} + 0, + 1 \text{ OH}_2\text{O} \dashrightarrow 4Fe(OH)_3 + 8H^+ \qquad [11]$$

If the conditions are reducing enough, then the production of sulfides by sulphate-reducing bacteria may lead to the precipitation of insoluble sulphide forms of iron and other metals (M) present:

$$Fe^{2+} + S^{2-} \dashrightarrow FeS\ (s) \qquad [12]$$

$$M^{2+} + S^{2-} \dashrightarrow MS\ (s) \qquad [13]$$

2.2 Maintenance of Anoxic Conditions

The critical question about using compost as a cover on pyritic tailings is whether it will maintain a permanent oxygen barrier and perpetually maintain reducing conditions in the tailings.

Pyritic tailings consume oxygen and thus function as the sink end of an oxygen diffusion gradient from the atmosphere. An oxygen barrier may involve chemical and biological processes which act as a competitive sink for oxygen, as in organic matter oxidation, leaving no oxygen to react with the tailings. Alternatively, a layer which offers a very high physical resistance to the diffusion of oxygen molecules will also function as barrier since the resultant oxygen flux for pyrite oxidation will be negligible. A layer of compost or other organic matter offer the potential to be both a physical barrier and an oxygen-consuming barrier.

Another potential benefit of compost is that its aerobic and anaerobic decomposition products, such as organic acids, may inhibit the growth and activity of the bacteria responsible for catalyzing pyrite oxidation processes and stimulate bacteria which can reduce oxidized compounds.

2.2.1 Compost Oxygen Barrier Models

Three designs for compost cover layers are presented, which appear from a review of the literature to satisfy many of the requirements for an oxygen barrier on tailings. The rationale for these models will be discussed in this chapter. In model A (Figure 5a), compost is ploughed into the upper layer of tailings, then a compost layer is placed on top of the tailings and permanently compacted by the weight of an overburden of sand and gravel. The cover layer of compacted compost will be moistened by precipitation and remain at least partly saturated with water, thus maintaining an anoxic environment in the tailings below. The decomposition of organic material above and within the tailings will set up a reducing environment which may reverse the oxidation processes which have occurred in the upper tailings. The compost layer may also function as a zone of low hydraulic conductivity which will discourage the downward mass flow movement of infiltrating water into and through the tailings.

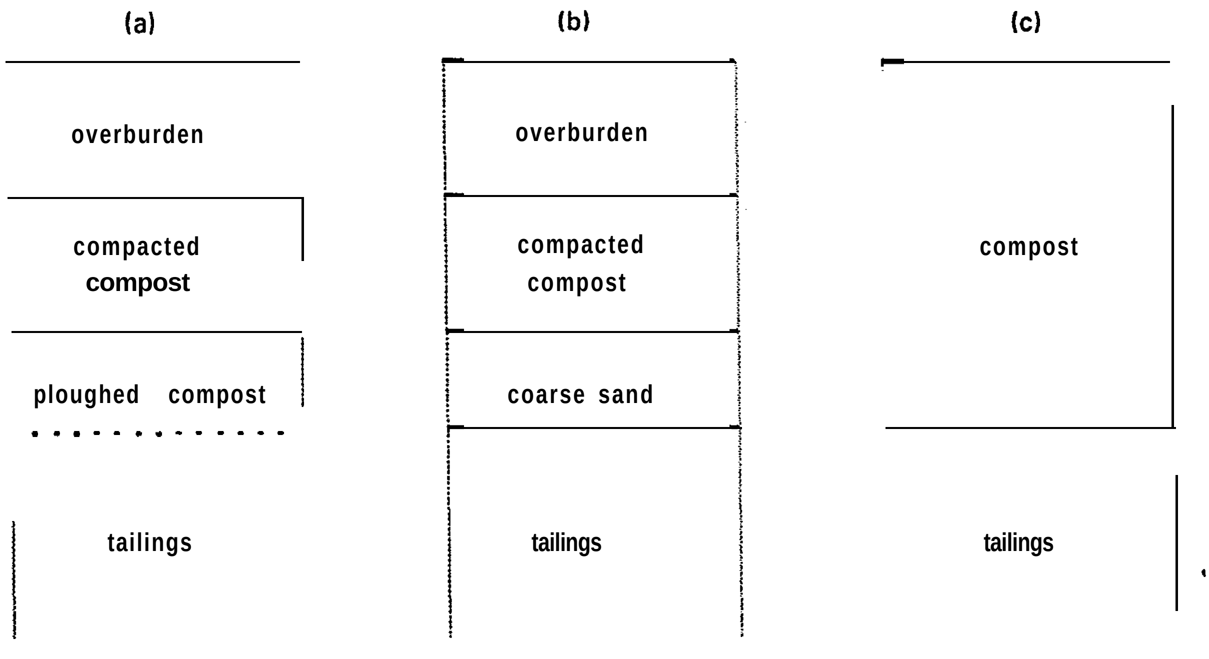

Figure 5. a) compost cover model A; b) compost cover model B; c) compost cover model C.

Similarly, model B (Figure 5b) has a layer of compacted compost and an overburden of sand and gravel, but it is isolated from the tailings by a layer of coarse sand and is not incorporated into the tailings. The coarse layer is designed to act as a capillary barrier (cf. Nicholson et *al.* 1989) and prevent the drainage of compost water into the tailings driven by the gradient of water tension in the tailings. In this manner the compost layer maintains saturation and anoxic conditions. Model C (Figure 5c) represents the simplest solution with only a thick layer (i.e. 2 m or more) of compost placed on the tailings. The weight of the compost itself would cause compaction of the bottom layers of compost next to the tailings. Without an overburden layer, however, the compost in model C would be susceptible to the greatest degree of atmospheric oxidation and erosion.

All compost models may also include the incorporation of other materials or organic wastes to modify the chemical or physical properties of the compost layer. It is assumed that stabiiization of the compost layer by revegetation is not a main objective of this research program, but it may proceed from the selection of an overburden layer and treatment suitable for plant growth.

In reviewing the literature on composts, it was clear that little work has been done on the physical properties of MSW composts or waste organic materials (cf. Gallardo-Lara & Nogales 1987). Most of the research emphasis has been placed on the processing and chemical suitability of aerobic compost for the agricultural and horticultural markets. There is virtually no information available on the behaviour of composted material in a saturated state. However, organic soils that have formed under waterlogged, oxygen-deficient conditions appear to share many physical and chemical characteristics with compost (Ingram 1978, Rowell 1988, Kennedy 1991). Thus, the soil science literature has been very helpful in defining many parameters and concepts relevant to the use of compost in tailings reclamation.

The literature on other organic materials, such as sewage sludge, sawdust and paper mill sludge, has also been consulted, both for concepts applicable to compost and also for information about the usefulness of these wastes in tailings covers. Many waste materials have already been field tested as soil amendments in the amelioration and revegetation of acidic mine spoils or other disturbed lands (Sutton & Dick 19871, but few studies have directly addressed the problem of designing an oxygen barrier or other techniques to prevent pyrite oxidation (Dyer 1984, Dave & Michelutti 1991).

2.2.2 Chemical Oxygen-Consuming Barrier

It is likely that MSW compost will initially have a high BOO, which will function as an oxygen-consuming barrier (Finstein et *al.* 1980, Gallardo-Lara & Nogales 1987, Boyle 1990). However, the oxidation of compost organic matter is a finite process which will decrease as labile components and small molecules are oxidired and humified (Stutzenburger et *al.* 1970). The long term oxidation of humic compounds will continue, but at a much slower rate. To maintain the compost layer solely as an aerobic oxygen-consuming barrier, fresh compost would have to be added periodically to increase the BOD or until the point when the depth of humic materials is great enough to maintain a sufficiently high decomposition rate and high BOD to be a perpetual oxygen barrier. Modelling of compost BOD in this type of cover layer application has not been done and the potential of compost as a perpetual oxygen-consuming barrier would have to be investigated experimentally.

2.2.3 Physical Oxygen Diffusion Barrier

It is well known that the primary transport mechanism for oxygen into a porous medium such as tailings or soil is by molecular diffusion through continuous gas-filled pore spaces (Nicholson et *al.* 1989). Molecular diffusion in air is very slow compared to convective transport and is affected by porosity, tortuosity (i.e. diffusion path length), temperature and any interactions between oxygen and the porous medium. Since molecular diffusivity of oxygen in water is 10,000 times less than in air, the effective gaseous diffusion coefficient is inversely related to the fraction of pore spaces filled with water. The effective diffusion coefficient typically decreases dramatically as the degree of saturation increases beyond 90% (Nicholson et *al.* 1989).

Oxygen can also penetrate the tailings dissolved in water which is flowing through the pore spaces. Microbial aerobic processes in tailings can be maintained at quite low dissolved oxygen concentrations characteristic of infiltrating oxygenated groundwater (Dyer 1984, Hammack & Watzlaf 1990). Thus, the control of groundwater flow into and through tailings must be considered in compost cover design. Reardon & Moddle (1985) ran water for 57 days through columns containing various depths of decomposed peat and uranium tailings in order to simulate 6 years of saturated flow conditions. There was virtually no difference in effluent water quality between the peat treatments and the control for saturated or unsaturated flow conditions. They concluded that dissolved oxygen (partial pressure > 2%) had penetrated through even the thickest peat layer (30 cm) and oxidized the tailings material.

Oxygen Diffusivity and Degree of Saturation

To design a permanent oxygen diffusion barrier, it is important to know under what conditions and to what extent an organic layer such as compost or peat will remain saturated with water, over at least part of its depth.

Reardon & Poscente (1984) studied the gas composition, pore water acidity, pore water carbon and decomposition in four wood waste piles in northern Ontario. The oxygen flux into the waste was found to be a direct function of the coarseness of the grain size. In fine-grained wood particles (<4 mm), oxygen was virtually absent below a depth of 50 cm. In ail four sites, O_2 and CO_2 varied inversely with depth, and the two sites with anoxic conditions not far below the surface had highly decomposed surface layers, but relatively unoxidized deeper layers. Oxygen partial pressures were less than 2% in the anoxic layers and moisture content determinations (done on one pile, on only one day) showed that the upper 55 cm layer was very wet. The wettest layer was also the most decomposed layer.

Reardon & Poscente (1984) estimated the rate of mass loss by integrating the gaseous CO_2 flux out of the pile. The model showed that the equivalent of 13 cm depth per year is being lost by aerobic decomposition. Using this mass loss rate, they calculated that the saturated, anoxic layer of wood waste would have to be at least 20 cm thick to last 1000 years. This longevity makes wood waste an attractive cover material for close-out of pyritic tailings. Consumption of oxygen by the oxidation of wood waste will also form an oxygen-consuming barrier, and this further supports the proposed models (Fig. 5). Reardon & Poscente (1984) also pointed out that the leaching of tailings heavy metals by reaction with specific compounds, such as organic acids and phenols from wood waste decomposition, is a concern to ground water quality that would have to be studied.

Peat has been suggested as a cover material which would create an oxygen barrier on pyritic tailings

(Reardon & Moddle 1985, Brown 1991, Winterhalder 1992). Swain (1978) showed that the porosity of horticultural peat compost is a function of the peat source, state of decomposition and the presence of other constituents (Table 1).

Table 1. Porosity of sand-peat composts (Swain 1978).

Compost Mixture	% Total porosity	% Air-filled pores
Moss peat (100%)	95	39
Moss peat (80%) coarse sand (20%)	80	29
Moss peat (80%) fine sand (20%)	76	17
Finn peat (100%)	95	4
Finn peat (80%) coarse sand (20%)	80	14

Although the difference between moss peat and Finn peat was not described, these data suggest that the particular compost composition may be important with respect to the moisture retention characteristics and that other amendments, such as fine sand, may enhance the degree of water-filled pores.

Typically, organic soils which have been drained (or which have a deep water table) have low bulk density, high porosity, good aeration and good infiltration (Farnham & Finney 1965). Peat soils are composed of a mixture of plant remains at different stages of decay. The fragments range from easily identifiable coarse plant residues to dark-coloured, amorphous, humic materials. The relative amounts of fibre and colloidal material have a marked influence on the physical characteristics of the bulk soil (Boelter 1969). For example, net mobilization or immobilization of nitrogen will be found in different peats, depending on a complex of factors including state of decomposition (Williams 1983).

In a partly decomposed peat, the pore space comprises more than 80% of a unit volume, and it is distributed in a fibrous matrix rather than a granular one (King & Smith 1987). The three-dimensional shrinkage of peat is caused by the collapse of large pores, that drain at low moisture tensions (i.e. high AEV). The shrinkage of pore space partially offsets the advantage to diffusion of increasing pore continuity, which occurs as pores drain in a fixed matrix. Relative (to free air) diffusivity in peat shows a linear increase with air-filled pore space (King & Smith 1987).

It is hard to predict the porosity of a particular compost, but it will likely be quite porous and there may be a porosity difference between cured and immature composts. In a study of aerobic and anaerobic sludges and their composted mixtures, Pagliai et *al.* (1981) found that all organic materials significantly increased soil porosity and aggregation in a manner comparable to manure, regardless of rate of application and initial water content. This suggests that all composts will be fairly porous.

Dearee of Saturation and Compost Water Balance

It is evident that a compost layer will not function as an oxygen barrier unless all pore spaces over part of its depth remain filled with water. Water retention or storage in the compost layer may be treated as a water balance (equation 14).

$$\text{Storage} = \text{Precipitation} - \text{Drainage} - \text{Evaporation} \quad [14]$$

All the terms on the right in Equation [14] are a result of transient properties and processes of the compost or the climate, so the water balance will always be a dynamic situation. The significance of the storage term to compost saturation depends on the physical characteristics of the compost under field conditions.

In the spring, most soils of northern temperate climates begin in a saturated condition. Since the soil thaws from the surface down, a high water table is usually maintained above the frozen saturated soil layer. A compost layer should, therefore, start the spring in a saturated condition. Some drainage and evaporation of water from the uppermost compost layer should be expected. Unless the year has far less than the average amount of snow and rain, then an engineered compost layer in the Boreal Forest should be able to retain a satisfactory amount of water if losses due to drainage and evaporation are minimized (cf. Munro 1984).

Poor infiltration of precipitation and excessive runoff are not expected to be problems in the functioning of a compost layer. Some peats are well known for their resistance to rewetting once they have partially or completely dried. In a comparison of various composts and peats, Valat et *al.* (1991) found fresh Sphagnum peat and manure-composts to be hydrophilic (i.e. wettable), whereas woody litter and decomposed peat were much more hydrophobic and resisted rewetting. They observed that in the drying process, peat colloidal material became irreversibly aggregated. The surface composition of MSW compost particles indicates that the ability to rewet will not be a problem; however, the degree of aggregation on drying and its significance to porosity remain to be investigated.

The maximum moisture-holding capacity of peats shows a wide range of values (100% up to 3000% of dry weight) and each peat has a different water retention curve as a function of soil moisture tension (Farnham & Finney 1965). The amount of water retained at low tensions is much greater than for a mineral soil, but this is a function of its greater porosity.

Unfortunately, organic soils begin draining at very low soil moisture tensions. The air entry value for salt marsh peat sediments is high, in the range of -18 cm of pressure head, which indicates that the largest pores will drain and air will infiltrate readily. as the material comes under a small soil water tension (Hemond & Chen 1990). The water retention characteristics and air entry value for compost materials are not known, but they are expected to fall into the range of parameters for some peat soils.

The rate of drainage will be dependent on the hydraulic characteristics of compost material and on water flow in response to gradients of water tension into the tailings and laterally through the compost layer. The design of the compost layer and other layers may be very important to maintaining water saturation.

The characteristics of the underlying (standing) medium were found to be important to water drainage from horticultural compost (Swain 1978). Good drainage is maintained by good pore continuity between the compost layer and the substratum, which should be of similar pore size distribution. Conversely, contrasting pore characteristics between compost and standing material leads to poor drainage (Table 2) and a likelihood of waterlogging and anaerobic conditions in the compost layer (Swain 1978). These data support the capillary barrier approach of model B.

Table 2. Percentage water loss from saturated compost layers with time and on different standing materials (Swain 1978).

Compost Cover Layer	Standing Material	Draining Time (hours)		
		2.5	5	24
peat-sand	gravel	10%	10%	12%
	coarse sand (15 cm)	20	19	21
	fine sand (15 cm)	31	34	39
peat	gravel	14%	14%	17%
	coarse sand (15 cm)	29	30	32
	fine sand (15 cm)	39	44	48

The hydrology of peat soils and bogs has been studied extensively and offers information that may apply to compost. Boelter (1969) showed that physical properties of peat, such as bulk density, water retention and hydraulic conductivity, are related to the degree of decomposition and how this determines the porosity and pore size distribution. He found that hydraulic conductivity decreased by two orders of magnitude (10^{-3} to 10^{-5} cm s^{-1}), bulk density increased by a factor of three and porosity decreased more than 10% over the range of decomposition and depth in the peat profiles.

Peatlands result from the accumulation of organic soils over long periods that result in a water body which is perched above the regional water table system and may be hydrologically separate from it (Gafni & Brooks 1990). The perched water table is a function of the build-up of organic matter which acts like a sponge with poor water flow out of it. The result is a dome-shaped water table within the peat, with water flow outward from the centre toward natural drainage points.

The rate of peatland water outflow is controlled by: a) the lateral hydraulic gradients caused by the difference in hydraulic head across the domed water table; and b) the hydraulic conductivity of the peat layers. Gafni and Brooks (1990) found that the hydraulic conductivity of peat decreases by one or two orders of magnitude with depth (e.g. 203 to 8.6 m day^{-1} over 50 cm depth), from fresh surface layers to highly decomposed layers over a metre [illegible] Hydraulic [illegible]ents were always steepest [illegible] at drainage gas, produced and restricted under pressure in the saturated lower levels, was occupying pore space and therefore reducing pore continuity for water flow. Brown (1989) reports similar results which support the methane hypothesis. There is the potential for methane production by fermentation in compost if strong reducing conditions are maintained (cf. Fig. 4).

Three studies of organic soils show the potential of compost as a saturated cover layer which can maintain anaerobic processes such as slow organic matter decomposition and the reduction and mobilization of iron. In a study of the long-term effects of peat debris on mineral soil morphology, Collins & Coyle (1980) found that a 7-10 cm layer of peat was sufficient to initiate gleying, (i.e. it led to partial exclusion of air, poor biological activity, increased wetness and soil structural collapse). The increased wetness of the humic-gley is attributed to the accumulation of moisture near the base of the peat layer because of the loss of aggregation in the mineral layer below. Some of the iron was in reduced form and was leached to lower profile positions where it oxidized and re-precipitated.

In soils with peat layers of 25-30 cm, rainfall and dew were sufficient to keep the surface layer moist while the middle layer appeared much drier and less humified (decomposed). Thus, due to high permeability and hydrophobism of the middle peat, the greater part of the incoming precipitation reached the basal peat layer but, due to lack of continuity of pores, did not flow any further. Decomposition products of this humified layer seeped slowly into the mineral soil below and led to impermeable massive sticky/plastic soil (Collins & Coyle 19801. These results suggest that the properties of peat as an anaerobic cover should be investigated in comparison to MSW compost.

The development of an ironpan layer in a humic podzol soil in Newfoundland was investigated by McKeague et *al.* (1967). The cementing material was found to be an amorphous, iron-fulvic acid complex arising from decomposition in the organic horizon and the reduction of iron in the upper, wetter part of the soil profile. But the lack of oxidizing conditions in the lower part of the profile containing the ironpan indicated that iron oxide was not forming and that the saturated peat surface layer was maintaining reducing conditions in the mineral horizons at least part of the time.

Pyatt & Smith (1983) found a thin ironpan in a peaty stagnopodzol soil in southern Scotland, which maintained saturated conditions in the peat layer above the unsaturated, oxygenated lower mineral horizons. They attribute the perched water table in the peat to its poor hydraulic conductivity. This situation is found typically in peat in the first 10 years after planting of the spruce plantation, before the trees moderate the extremely wet soil conditions.

Swelling, Shrinkaae and Compaction

No research appears to have been done on how well an exposed compost layer will retain its structure over a large range of water contents and with decomposition. Many peats are known to crack on drying but Pyatt & John (1989) found that, in contrast to pseudofibrous and amorphous peat samples, fibrous peat (ranging from tough stringy fibres to almost raw *Sphagnum)* resisted cracking. The textural qualities of MSW compost or raw organic material are variable and their resemblance to peats in unknown. However, cracks in the compost layer caused by swelling and shrinking would be very detrimental to the maintenance of an anaerobic barrier by providing large channels for oxygen diffusion and perhaps atmospheric convection to the tailings surface. One solution is to compact the compost with an overburden layer to protect and stabilize it.

Broman et *al.* (1991) created a one metre sealing cover on tailings using a mixture of paper mill sludge and fly ash. The cover permeability was greatly reduced by compaction (i.e. 10" cm s^{-1} decreasing to 10^{-8} cm s^{-1} under 11 kPa overburden load) and this was most easily achieved by placing a protective layer of wood waste or gravel, which is later to be grass-seeded. The 0.5 m overburden layer has also prevented freeze-thaw cracking and erosion of the sealing layer. In addition, the leachate from the sludge-ash layer contained compounds with BOD and is expected to aid in preventing oxidation of tailing sulfides.

Currie (1984) studied gas diffusion in clay loam soil as a function of wetting and compaction. He concluded that, if soil samples are compared at the same water potential (i.e. soil moisture tension), the more dense soil will have a greater volumetric water content and poorer aeration by gaseous diffusion than uncompacted soils (e.g. 38% less in clay loam).

Swain (1978) observed that either decomposition or compaction of horticultural compost will significantly change its physical properties. Table 3 shows that compaction decreased total porosity by a few percent, but the percentage of water-filled pores increased substantially. He did not quantify the degree of compaction achieved.

Table 3. Physical comparison of compacted and uncompacted compost. (Swain 1978).

Compost	% Solid	% Total porosity	% Air pores	% Water pore5
normal	22	78	39	39
compacted	31	69	8	61

Other organic materials also undergo substantial changes in their physical properties under compaction. Chow and others (1992) studied the effects of compaction on the hydrologic characteristics of agricultural Sphagnum peat. The optimum moisture content for achieving maximum bulk density decreased with increasing compaction pressure because compaction reduced the volume and continuity of large pores. In response to this large pore reduction, saturated hydraulic conductivity decreased more than three orders of magnitude (i.e. 10^{-2} down to 10" cm s^{-1}) as the bulk density increased from 0.10 to 0.24 g cm^{-3}. However, not even the highest compaction pressure, 100 kPa (i.e. 1 kg cm^{-2}), resulted in the peat sample becoming totally saturated. After a short compaction treatment, the unburdened peat showed a major increase in moisture retention and only a partial recovery of swelling on rewetting because of the increase of small pore volume and reduction in large pore volume. Relative oxygen diffusivity will also be decreased because of poorer pore continuity and greater tortuosity under compaction (Currie 1984, Gupta et *al.* 1989). They did not perform or comment on the effects of a long compaction treatment, as would apply to the proposed compost cover layer models.

An overburden layer on top of the compost would also have the benefit of reducing evaporative water loss. The solar radiation absorption by a light-coloured sand/gravel surface would be less than for the dark, porous compost surface. Less absorbed radiation results in less heat energy stored and thus a lower temperature at the evaporating surfaces to drive evaporation. The presence of a relatively coarse, dry sand/gravel layer would also impose a diffusion barrier for water vapour and oxygen flux to and from the moister compost layer. An exposed compost layer such as in model C (Fig. 5c), though, would probably dry quickly at the surface and be self-mulching to some extent. Establishment of vegetation, especially trees, on the overburden layer would have to be carefully considered from the viewpoint of increased evapotranspiration from the compost layer and the effect that would have on the water balance (King et *al. 1986).*

The implications of the discussion above for compost layer design have been reflected in the compost layer models (fig. 5). The requirement to maintain saturated conditions in the compost layer is satisfied by compaction of the compost, which distributes stored water so that moisture is held in relatively small pores and fills all the air voids, at least at the base of the layer. The overburden layer allows precipitation to infiltrate the compost layer, but discourages evaporative water loss. Moisture is retained in the compacted compost because of poor drainage due its low hydraulic conductivity. As the compost further humifies, its hydraulic conductivity should be further reduced.

In model A (Fig. 5a) the compost layer has close contact with the tailings through incorporation of compost material into the upper tailings layer. This may promote drainage of the compost and be detrimental, so it may be necessary to isolate the compost hydraulically from the tailings with a coarse layer (Fig. 5b) which functions as a capillary barrier (cf. Nicholson et *al.* 1989). A disadvantage of this approach, besides greater complexity and cost, would be the chemical isolation of the compost layer from the tailings. The possible ameliorative role of compost in tailings rehabilitation will be discussed next.

2.3 Chemical Processes in the Compost-Tailings System

A number of studies have looked at chemical approaches to suppressing pyrite oxidation, in both aerobic and anaerobic conditions. In many cases, a key ingredient was the addition of limestone or other alkaline agent to raise the pH and suppress the activity of aerobic, acidophilic, sulphur-oxidizing bacteria. Other chemical treatments which have been shown to inhibit acid production by pyrite oxidation all interfere with the chemistry of iron in the tailings (Pulford 1991). They may act by precipitation, which removes iron from solution, or by complexation, which either keeps the iron in a non-reactive form or inhibits the oxidation of ferrous to ferric iron.

Scanlon et *al.* (1973) conducted a four-year study on the use of municipal compost in revegetation of coal mine spoils. The composted plots showed a marked decrease in acidity (e.g. grass plot pH rose from 3.8 to 6.9 in four years) and good plant establishment and growth. A problem with die-off of Virginia pine seedlings at high compost rates was attributed to toxic products of partial digestion in the composting process, although these substances were not identified. Kuster & Schmitten (1981) reported that various extracts present in fresh MSW were anti-microbial, but that their efficiency decreased with degree of decomposition and no new anti-microbial compounds were formed.

Hoving & Hood (1984) have shown that a 30 cm soil layer is sufficient to impede pyrite oxidation. They also concluded, however, that whereas the use of a soil cover as an oxygen barrier is effective on fresh pyritic material, oxidation is difficult to stop once it has started in old tailings. Limestone layers proved to be ineffective in improving leachate quality.

Ameliorative Effects of Organic Matter

Once reducing conditions are established in the tailings, ferric oxides which are present may be reductively dissolved by three mechanisms: acidity (Equation 151, organic compounds (Equation 16) and bacteria (Equation 17) (Anderson & Christensen 1988, Francis & Dodge 1990).

$$Fe(OOH)_{(s)} + 3H^+ + e^- \longrightarrow Fe^{2+} + 2H_2O \quad [15]$$

$$Fe(OOH)_{(s)} + \text{organic leachates} \longrightarrow Fe^{2+} \quad [16]$$

$$Fe(OOH)_{(s)} + \text{bacteria} \longrightarrow Fe^{2+} \quad [17]$$

Trace metals adsorbed onto iron precipitates will be mobilized (Francis & Dodge 1990) and Fe^{2+} that is produced can lead to more acid production if it is reoxidized (Equation 3). The different pathways of microbial oxidation of organic matter with concurrent reduction of Fe(III) and Mn(IV) are reviewed by Lovley (1991) and shown diagrammatically in Figure 6.

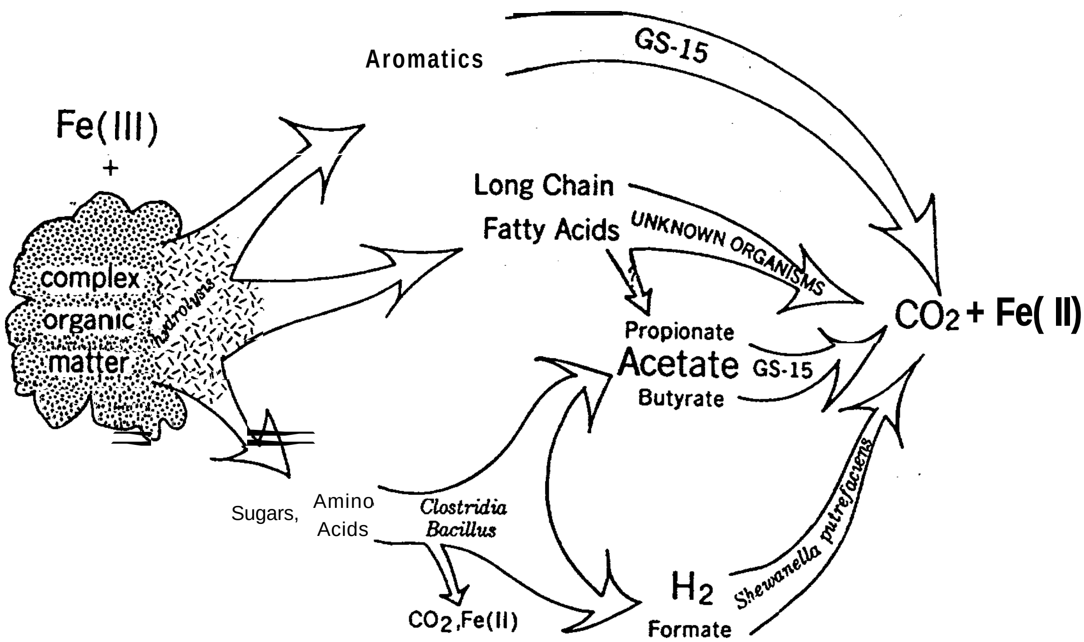

Figure 6. Model for the oxidation of complex organic matter with Fe(III) serving as the sole electron acceptor, with examples of microorganisms that may catalyze the reactions (from Lovley 1991).

In the proposed compost models (Fig. 5), most or all of the compost volume will not be in direct contact with the tailings and the cover is designed to inhibit the drainage of water and oxygen into the tailings. However, close contact between the bacteria and the oxidized tailings, in some systems, seems to be essential for reductive dissolution of the iron oxide (Jones et *al.* 1983, Arnold et *al.* 1988). This would be an advantage of model A where there is continuity between the compost cover and the compost-amended upper tailings. The compost layer in model B may be hydraulically isolated from the tailings, but under supersaturated conditions in the compost, water flow into the tailings should occur taking with it any bacteria and dissolved compounds. The hydraulic properties of a compost layer under different conditions must be investigated for both models in order to understand the potential for chemical amelioration.

Decomposition of organic matter releases carbohydrates and other organic substrates which are important to respiration in the sulphate-reducing bacteria (Rowell 1988) and some organic compounds can reductively dissolve ferric hydroxide precipitates without bacteria (Lovley 1987).

Eger (1992) found that a wide variety of organic waste material could be used as the organic substrate for sulphate-reducing bacteria, including 45 day old municipal compost, composted yard waste, horse manure and wood shavings. The highest rates of sulphate reduction (75%) in AMD waters were seen in the municipal compost treatment, apparently because the compost supplied more labile organic compounds than the other substrates. The results with compost compared favourably with wetland treatment systems employing a mushroom compost substrate (e.g. Dvorak et *al.* 1991). Sulphate reduction produced hydrogen sulphide, which was largely responsible for precipitating AMD nickel, copper, cobalt and zinc (Equation 12) with greater than 90% efficiency.

Little information is available on the interaction of iron with organic substances derived from pyritic spoil (Pitchel et *al.* 1989). Such transformations may be significant to the chemistry of pyritic mine spoils because Fe^{3+}, under certain conditions is an important oxidizing and solubilizing agent for pyrite, a reaction sometimes called indirect pyrite oxidation (equation 4). Pitchel *et al.* (1989) found that water soluble sewage sludge extract promoted oxidation of Fe^{2+} to Fe^{3+}, which then becomes unavailable for pyrite oxidation due to complexation with organic ligands. The ligand-Fe complex is very mobile, and the iron may precipitate at the right pH. In contrast, the reaction of humic acids and Fe^{3+} results in Fe-oxyhydroxide precipitates.

Further work (Pitchel & Dick 1991) showed that other organic products, such as sewage sludge compost, paper mill sludge compost, water-soluble compost extracts and pyruvic acid, removed almost all the soluble Fe either by preventing Fe oxidation or by complexation of Fe^{3+} with organic compounds. Total SO_4^{2-} and other sulphur compounds were also reduced, up to 54% in the sewage sludge treatment. These ameliorative results were separate from any benefits from buffering of pH.

Loomis and Hood (1984) mixed anaerobically-digested sewage sludge with pyritic mine soil. They concluded that the sludge reduced AMD by increasing the pH, thus causing ferric hydroxide to precipitate (Equation 5). They suggested that the precipitate coated the pyrite granules, thereby reduced their surface area and prevented the continued oxidation reaction sequence.

Backes *et al.* (19881 found that additions of chicken manure 'and chipboard wood wastes to 4% pyrite spoils substantially decreased titratable acidity and iron in leachate solution, the manure having a greater effect than the wood wastes. They concluded that the oxidation of pyrite or of Fe^{2+} to Fe^{3+} was inhibited. They suspect that ferrous and ferric iron became chelated to soluble and insoluble components of the organic material and thus were unavailable for the processes of pyrite oxidation. However, no measurements of bacterial activity were made to investigate if bacteria-catalyzed oxidation processes were affected.

The type of decomposing organic matter and its oxidation products may lead to very specific chemical interactions. Vaughn *et al.* (1984) used a variety of softwood and hardwood wastes to remove ferrous iron from the drainage water in peaty soils and acidic soils. They concluded that water-insoluble tannins in the conifer bark immobilized the Fe(II) and avoided need to employ commercial phenols which are potentially toxic in the environment. Phenols and other aromatic compounds released from compost into tailings may play a significant role in the bacterial reductive dissolution of Fe(III) oxides (LaKind & Stone

1989, Lonergan & Lovley 1990). However, a review of work on reductive dissolution of Fe(III) oxides indicates that abiotic, non-enzymatic reduction by various organic compounds is probably not a significant process in most environments (Lovley 1987).

Sewage sludges are usually near neutral pH and, when applied to acidic mine spoils, increase the pH for several years, possibly as a result of increased ammonia and ammonium concentrations from anaerobic decomposition (Sutton & Dick 19871. Sludges also improve the soil by increasing the organic carbon content, plant available nutrients and cation exchange capacity. Negative effects of sewage sludge include increased levels of heavy metals and salts, especially at low pH.

The mixture of compounds in MSW compost and their decomposition products appear to offer considerable potential for the amelioration of pyrite oxidation products in the tailings. The trends shown in the literature towards lower acidity and improved leachate quality are more important than the quantitative results. Further work on compost-tailings chemistry for a specific site is required to assess these benefits for the compost cover models that are proposed (Fig. 5). The major variables to be investigated include compost quality (i.e. maturity and contaminants), compost physical properties and the oxidation state of the tailings.

2.4 Compost Decomposition and Longevity

Even if one or both of the compost cover models functions effectively as an oxygen barrier (Fig. 5), the goal of tailings abandonment is to suppress pyrite oxidation and avoid AMD forever. Thus, the longevity of the compost layer under continuing decomposition processes also becomes an important issue.

Molot (1992) recommended the use of MSW compost only at the bottom of shallow ponds on tailings, where decomposition will be kept to extremely low levels in anoxic conditions and where tolerant aquatic vegetation may be established to stabilize the organic sediments. This is a good solution to the problem of long term compost decomposition, but it requires that the impoundment of water on the tailings be a permanent, self-perpetuating solution - a constructed ecosystem. Brown (1991) also advocated the establishment of permanent, living oxygen barrier on tailings by transplantation of peat material to a suitable saturated tailings site. However, peat will be replaced quickly by other plant communities if the high water table is not maintained.

Rates of Organic Matter Decomposition

It is not known how the composition of MSW compost will affect its rate of decomposition in the field. One study of cornposting of eucalypt bark (Ashbolt & Line 1982) found that a high C/N ratio inhibited decomposition, especially of the cellulose component (Table 4). This suggests that the addition of a material with a very high C/N ratio, such as sawdust, may be beneficial in inhibiting bacterial decomposition of compost.

Table 4. Percentage mean loss of compost components after 35 days of cornposting (after Ashbolt & Line 1982)

Component	Initial C/N Ratio 45	65
total nitrogen	16%	8 %
cellulose	55	2
total weight	26	14
final C/N ratio	17	18

Peat bogs provide perhaps the best case estimates, and organic agricultural soils the worst case estimates, of the rate of organic matter decomposition in the fieid. Peat bogs arise in waterlogged conditions because decomposition rates have been less than rates of plant production. Some peat samples from perpetually waterlogged layers have been dated at 10,000 years in some European bogs (Heal *et al.* 1978). As soon as peat is drained, rates of CO, production increase by a factor of ten due to the aerobic conditions and increased temperature regime (Moore & Knowles 1989).

However, water content still has an important effect on decomposition rate. Heale et *al.* (19781 observed that below 600% moisture content, loss of mass in peat is reduced. The moisture contents in the top 10 cm layer, in the bog studied by Lieffers (19881, ranged from 320 to 560%, so the author concluded that the sub-optimal moisture content for decomposition in the surface layer somewhat countered the positive effects on aerobic decomposition expected following drainage and increased substrate temperature.

Heal et *al.* (1978) found that microbial respiration in peat litter was positively affected by moisture content below 100% but showed a maximum rate plateau from 100% to 600% water content. On much of the 2 m deep blanket peat studied, the water table was within 20 cm of the surface. Reducing conditions were strongest in the 10-20 cm zone and the zone of lowest redox potentials coincided with the depth within which the water table fluctuated (Urquhart & Gore 19731. Clymo (19781 emphasized that the rate of decomposition of organic matter declines markedly as it passes from the aerobic surface zone into the anaerobic conditions below the water table. Rates of decomposition decreased by 3-6% per centimetre depth in the top 20 cm of the peat bog.

Ivarson (1977) observed that *Sphagnum* litter decomposed quite a bit more slowly than finely ground white pine, oak and maple leaf litter. The rate of peat decomposition was much greater in the surface layer than in the 15-41 cm sublayer. Given and Dickinson (1975) have suggested that *Sphagnum* contains specific inhibitors, such as phenolic polymers, that restrict microbial decay and contribute to the preservation of peat. Phenolic polymers of higher plants, which are structurally similar to those of *Sphagnum,* inhibit decomposition of readily-degradable compounds, when incorporated with soil (Lewis and Starkey 1968). The occurrence of substances in MSW compost which inhibit decomposition is not known.

Mirza and Irwin (1964) estimated that recently drained and cultivated muck soil in southern Ontario loses over 3 cm depth per year (even though being frozen for 5 months each year) mostly by biological decomposition. A lower rate of 2.07 cm per year was estimated by Millette (1976) for cultivated organic soils in the Ottawa and St. Lawrence valleys, Scanlon *et al.* (1973) found that MSW compost applied to mine spoil in Tennessee at a rate of 14 tons per acre had disappeared in two years. A 26 ton per acre rate resulted in some humified organic matter and 50 tons per acre left substantial residue and a humus layer after two years. Studies on MSW cornposting (Stutzenber et *al.* 1970, Suler & Finstein 1977) found that the rapid aerobic decomposition of compost occurs only at high temperature (i.e. above 50°C) because of the exothermic, self-heating oxidation processes of thermophilic bacteria and fungi. Typically 40% of the original cellulose is left in the mature compost product after 7-8 weeks. A compost layer in the field will likely decompose much more slowly because of cooler temperatures and other suboptimal conditions.

Clearly, a compost cover layer could not withstand completely aerobic degradation for many years and continue to function as an oxygen barrier. The compost layer in the three cover models being considered is expected to stay largely saturated with water for the non-freezing part of the year. As a result, a major part of the compost will be subject to a slower rate of decomposition by anaerobic processes.

Anaerobic Decomposition

Finstein et *al.* (1980) reviewed the processes of anaerobic compost production and sewage sludge digestion. They identified three stages in anaerobic digestion:

1) solubilization of polymers such as carbohydrates, proteins, lipids and fats;
2) acid formation from fermentation of glucose and amino acids;
3) methane production by methanogen bacteria which slowly break down organic acids and produce methane gas, if the pH is near neutral.

They suggest that anaerobic digestion is inherently an unstable process because acid forming bacteria are slowly replaced by methanogens as pH increases. But a negative feedback loop will lower pH if acid decomposition by methanogens lags behind the acid production of other bacteria. Methanogens are also sensitive to certain heavy metals and organic compounds. Commercial anaerobic decomposition results in 50-90% decrease in sludge solids by gasification and liquefaction. The solubilization of nitrogen and phosphorus compounds greatly increases the pollution potential of any effluent and produces a high BOD. It is difficult to predict how much of the compost mass will be decomposing anaerobically but it will certainly be a function of the portion of the layer near full saturation. Anaerobic decomposition in the absence of significant drainage does not seem to produce any problems when compared to aerobic decomposition. The slower rate of anaerobic decomposition may prolong compost layer usefulness as an oxygen barrier.

Erosion Problems

Erosion problems with compost on tailings (cf. Scanlon et *al.* 1973, Gallardo-Lara & Nogales 1987) would likely be prevented by the protection of the overburden layer in the proposed models (Fig. 5). In the longterm, revegetation of the overburden would be advantageous for its stability but aeration and breakup of the compost layer by roots will have to be considered as a potential problems.

It is not known to what extent these aerobic and anaerobic decomposition processes will occur in a compost cover layer in the field, but the longevity of the design will depend on whether enough stabilized compost survives to maintain a perpetual oxygen barrier. The protective overburden layer on the compost may turn out to be very important, not only for compost compaction and erosion control, but also to reducing decomposition by serving as both a partial oxygen and water vapour diffusion barrier and as insulation against high surface layer temperatures.

2.5 Summary

The problem of acid mine drainage from the oxidation of pyritic tailings may be addressed by imposing anoxia which will result in the maintenance of reducing conditions. Under reducing conditions, sulphate is reduced by bacteria to hydrogen sulphide, while iron and other metals are precipitated as sulphides and acidity is lowered. Under strong reducing conditions, oxides already present in the tailings may be reduced but this will mobilize, in the short term, trace metals adsorbed or coprecipitated with iron or manganese. Bacterial require organic matter as an. energy substrate, producing a variety of organic and inorganic compounds in the process.

Anoxic conditions may be established in the tailings by submersion in water and the addition of organic matter as a substrate for reducing bacteria. However, in tailings sites where impoundment of water is too expensive or difficult to do, an oxygen barrier on the tailings could be established by an impermeable dry cover, a water-saturated layer or a material which chemically consumes oxygen or physically limits oxygen diffusion from the atmosphere as a result of its high water content. The efficacy of water in preventing oxygen penetration to the tailings is based on the fact that the diffusivity of oxygen in water is 10,000 times less than in air.

Three models of water-saturated oxygen barrier are proposed (Fig. 5) which employ MSW compost as an oxygen-scavenging layer, and as a physical barrier to oxygen diffusion by maintaining a condition of high water saturation. Municipal compost, or some other suitable organic waste, may require modification of its physical properties by compaction under an overburden layer in order to maintain a condition of high moisture saturation. Chemicals from the decomposition of organic matter in the compost that is ploughed into the upper tailings may also ameliorate AMD by reductively dissolving existing oxides.

The critical issues to be addressed by experimental studies are the water balance of the compost-tailings model and its maintenance of anoxic conditions, the activity of compost in reducing tailings oxides and the expected longevity of the compost layer during long term decomposition.

3. QUALITY ASPECTS OF MSW COMPOST

The use of large quantities of MSW compost for tailings reclamation raises questions about its possible impacts on the environment, particularly aquatic systems, and potential hazards to human health. Municipal waste has been controlled by various levels of government regulations for decades, but MSW compost has only recently been viewed as a beneficial by-product of the MSW process. Aspects of the production, content, safety and reactivity of compost have been examined only in the last few years (Dillon & Cal Recovery Systems 1990, Curtis et *al.* 1991, OMOE 1991).

3.1 Composting Policy and Regulations • Ontario

At this time, there are no Federal cornposting policies, standards, regulations or guidelines which apply to Ontario. On the other hand, several Ontario statutes do apply to cornposting operations.

In the 1960's and 1970's, incineration was considered an important component of waste reduction, with potential side benefits of energy or heat generation. However, since this time, concerns over emissions from incinerators and ash disposal problems have resulted in these technologies being virtually eliminated as waste reduction options. The Government of Ontario has been increasing its efforts in the 3R's (i.e. reduce, reuse, recycle) area, with cornposting playing an important role (OMOE 1991). Ontario's goal is to divert 25% of the waste from landfill by 1992, with a 50% reduction of waste by the year 2000 (Massachusetts and California also have these targets). Consideration is being given to speeding up this schedule (Molot 1992).

To achieve these goals, two significant regulatory initiatives. have been made. In October 1991, the Ontario Government released Bill 143 "Waste Management Act" with an accompanying Initiatives Paper #1 entitled "Regulatory Measures to Achieve Ontario's Waste Reduction Targets". Bill 143 has recently undergone a period of public consultation. This is enabling legislation, with amendments to the Environmental Assessment Act, the Environmental Protection Act and the Municipal Act. Regulations are being drafted for release in the fall of 1992 to establish enforceable reduction goals and compliance time frames for individual geographic areas and specific industrial and municipal sectors (OMOE 1992).

Cornposting will have to be a major component of recycling efforts if the provincial reduction targets are to be met. The numerous 3R's activities are having an impact on the composition of MSW making it more difficult to predict the compost characteristics and quantities and also plan the compost plant specifications. Additionally, there is some community concern that the compost derived form municipal waste may be contaminated by a wide variety of toxic substance and pathogens, thus the use of compost is generally viewed as an environmental risk. The contamination problems in MSW compost generally arise from improper feedstocks and poor production methods (Dillon & Cal Recovery Systems 1990, Curtis et *al.* 1991).

This uncertainty has led to the Ontario Ministry of the Environment (OMOE) "Guideline for the Production and Use of Aerobic Compost in Ontario, 1991" (Appendix C). The guideline specifies siting criteria, operating requirements, monitoring requirements, and compost quality specifications. The guidelines are perhaps the strictest in North America and are based on agricultural food production as the major market for high quality MSW compost (Hanson 1991).

Compost products are segregated into three main categories:

I. *Unrestricted* use compost is a commercial product that does not pose any risk to health or the environment. Table 5(a) gives the maximum concentration of metals and PCB's allowed on a dry weight basis. An important,.demanding feature of these specifications is that the metal content of each raw material put into composting also shall not exceed the final compost concentrations;

II. *Controlled composts* fail to meet one or more of category I requirements but has levels of base metals, PCB's and non-biodegradable particulate matter within limits specified in Table 5(b). These composts may be used on urban soils and must be monitored and inspected by OMOE;

III. *Processed organic waste products* are composts which fail to meet the criteria for category I or II and are controlled under Regulation 309 of the Environmental Protection Act.

Table 5. Ontario quality specifications for: (a) unrestricted use compost; (b) controlled use compost (from Gies 19924.

(a)

Metal	*Concentration (mg/kg dry wt)*
Arsenic	10
Cadmium	3
Chromium	50
Cobalt	25
Copper	60
Lead	150
Mercury	0.15
Molybdenum	2
Nickel	60
Selenium	2
Zinc	500
Organic Chemical	
PCB	0.5
Nonbiodegradable Particulate matter	*Concentration (% dry wt)*
Plastic	1.0
Other (total)	2.0

(b)

Metal	*Column A Concentration (mg/kg dry wt)*	*Column B Maximum Allowable Metal Concentrations in Soil*
Arsenic	20	14
Cadmium	4	1.6
Chromium	50 25	120
Cobalt		20
Copper	100	100
Lead	500	60
Mercury	0.5	0.5
Molybdenum	3	4
Nickel	60	32
Selenium	2	1.6
Zinc	500	220
Organic Chemical		
PCB	0.5	
Nonbiodegradable Particulate Matter		*Concentration (% dry wt)*
Plastic		1.0 (oversize 8 mesh)
Other (total)		2.0 (oversize 8 mesh)

Under the Environmental Assessment Act, compost facilities handling less than 200 tonnes per day of residual waste generation from the facility are exempt from the Act. However, if the Minister deems the site to be environmentally significant, this limit may be waved and an Assessment can be required.

Part V of the Environmental Protection Act and Ontario Regulation 309 govern the disposal and processing of wastes at waste disposal sites for which Certificates of Approval are required. Compost processing is defined as a Waste Disposal Site (Processing) but is not a final disposal site, as the product is utilized elsewhere. Hearings are not mandatory, but are at the discretion of the OMOE Regional Director. "Permit by Rule" is a streamlining process which is being developed and expected to be in place in 1992. This procedure will exempt some projects from full Environmental Protection Act, Part V, Approvals.

Portions of the guidelines are waived for leaf and yard waste composting due to the lower risk of contamination from this type of cornposting. With the release of new regulations in the fall of 1992, composting of leaf and yard waste and recycling of all newsprint, cans, glass and maybe plastics will be mandatory by 1993 for all Ontario municipalities with a population over 5,000 (OMOE 1992).

If the site and compost do not meet the guideline specifications, then the compost will be designated as a processed organic waste and must be handled under Regulation 309. This means that Waste Disposal Site Approvals will be required for sites which receive the compost. If all approvals and Compost Guideline specifications are met, the compost will be considered a commercial product, thus avoiding the need for site and system approvals for the site of application.

Air Management Regulations under the Environmental Protection Act will require composting facilities to obtain Air Certificates of Approval. Standards for all airborne emissions, noise and odour will apply and may require treatment and/or control systems with the associated approvals.

In addition to the Acts mentioned above, proponents of composting facilities should also be aware that portions of the following Acts also apply:

- Ontario Water Resources Act
- Consolidated Hearings Act
- Planning Act
- Expropriation Act
- Fertilizers Act

Details of how these acts apply may be seen in the Guideline document (Appendix C). The Guideline also details some of the compost quality requirements of other jurisdictions. It is noteworthy that the Ontario standards have set the lowest permissible concentrations for heavy metal and other components of any international jurisdiction. This will make quality control for waste collection and composting manufacturing very critical. It has the potential to limit the amount of waste which is diverted to cornposting, to limit the potential utilization of compost and add significantly to the cost of compost production.

3.2 Composting Policy - Municipal

Composting production is becoming an important component of municipal integrated waste management strategy. Since compostable waste can comprise up to 75% of the MSW stream (Fig. 3), significant diversion of material from landfills can be achieved by cornposting. Quality compost should also have commercial value, so that its sale may generate revenue to offset a small portion of its cost of production. The landfill diversion is being driven by the provincial goals, stated above, and by the difficulty municipalities are having in siting new landfills as existing ones fill up.

However, in most municipalities composting is a new, untried technology which must be studied and carefully planned to ensure its success. A composting facility for a city of 100,000 may cost several million dollars, depending on the level of technology (R. Cave and Associates 1991). Each of the several Metro Toronto compost facilities being planned is estimated to cost $35 million, exclusive of land costs (Molot 1992). Cornposting, therefore, is very much an economic decision within the context of an integrated waste management strategy, which, in Ontario, is being directed by provincial policy and regulations.

3.3 Production Aspects of Compost Quality

Successful aerobic compost production depends on providing microorganisms with the optimal physical environment and chemical resources they require. Compost producers must control or monitor temperature, aeration, particle size, moisture content, nutrient balance (C/N ratio) and pH. The intended product is a stable, fine-grained, non-toxic, largely organic material with chemical and physical characteristics within a certain range of values (cf. OMOE 1991, Dillon & Cal Recovery Systems 1990). The OMOE report "Cornposting, A Literature Study, 1989" (Dillon & Cal Recovery Systems 1990), provides a comprehensive review of all aspects of aerobic MSW cornposting.

Temperature

Temperature in compost is an important point of control in compost production since it affects the rate and type of decomposition processes that can occur. The net heat retention of the compost mass is the sum of the heat production from exothermic microbial reactions and the rate of heat loss to the outside. The more insulated a compost mass is (i.e. low bulk density), the more heat it will retain and the higher will be the temperature (Yhland & Karlsson 1971). Compost technology used to try to achieve the highest possible temperature (i.e. >70°C) to maximize decomposition rate and the destruction of pathogens and hazardous compounds. But extensive work on cornposting quality and efficiency has shown that the optimum temperature range is in the region of 60-65°C (Finstein et *al.* 1984, OMOE 1991).

The chemical and microbial changes during composting may be viewed as four phases which are a function of compost temperature and type of microbial activity (Figure 7).

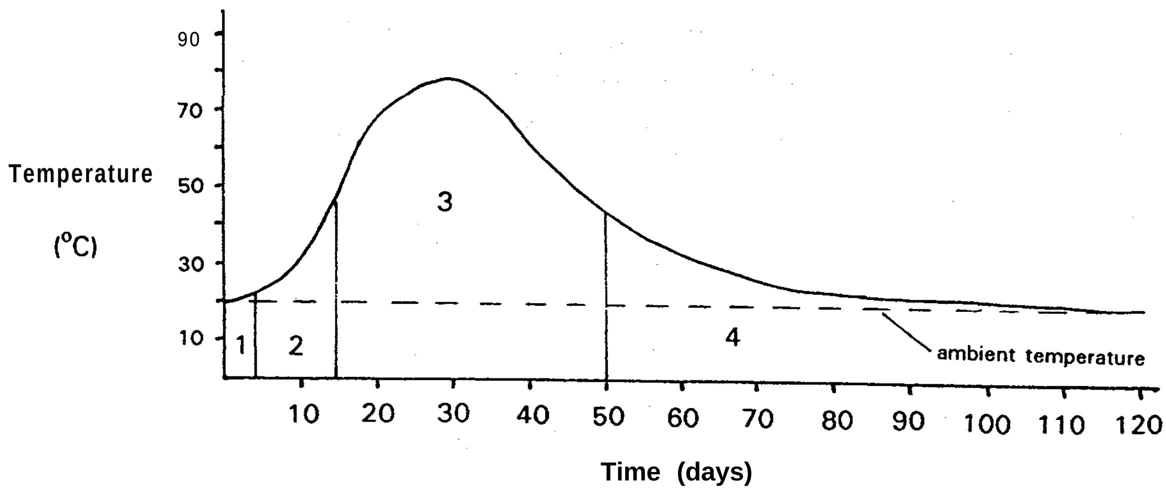

Figure 7. Temperature phases of the cornposting process: (1) latent phase, (2) mesophilic phase, (3) thermophilic phase, (4) maturation phase. (after Curtis et *al.* 1991).

In the latent phase, the temperature is near ambient and the microorganisms are acclimating to their environment and beginning to multiply. The mesophilic growth phase corresponds to a rise in temperature to about 45°C caused by rapid growth and exothermic metabolism of mesophilic ("medium temperature loving") bacteria. Above 45°C mesophilic bacteria are inhibited and replaced by thermophilic ("high temperature loving") bacteria which increase the temperature to the 60-75°C range. The thermophilic phase declines as the readily-decomposable carbohydrates and amino compounds are used up. The long maturation phase is characterized by decreasing temperature as thermophilic bacteria decline and slower decomposition of secondary compounds by various mesophilic microorganisms becomes predominant.

A compost layer on tailings (Fig. 5) would lose heat quickly to the mineral layers beneath and above it, so that temperatures and decomposition rates would be below the optimum. A high moisture content in the lower part of the compost layer will be conducive to heat loss by increasing the thermal conductivity and this may be inhibitory to microbial activity (e.g. Yhland & Karlsson 1971). Cooler temperatures will also decrease, to a small degree, evaporation from the top of the compost layer, and thus- improve the water balance.

Aeration and Particle Size

Aerobic composting has a great requirement for oxygen because of biological oxygen demand of microbial cellular respiration. In the absence of sufficient oxygen, some bacteria can produce energy from substrates by anaerobic respiration or fermentation, however, this is usually a slower form of decomposition with different chemical products (Finstein et *al.* 1980). Aerobic cornposting requires small-size particulate material (e.g. < 25 mm) so that there is a high surface area to volume ratio for oxygen penetration (OMOE 1991). Size reduction of MSW is usually accomplished with shredders, grinders or cutters. Sometimes another material, called a bulking agent, is added to increase feedstock porosity and reduce its bulk density in order to achieve better aeration.

Conversely, compaction of material can decrease porosity and aeration. The result will be a inhibition of aerobic decomposition, if oxygen diffusion becomes limiting. In the current compost layer models (Fig. 5), we are trying to greatly decrease the aerobic decomposition rate and induce anaerobic decomposition through compaction and saturation of the compost. The overburden layer will also prevent convective air movement from reaching the compost and we might also expect that odour will be less of a problem.

Moisture

Bacteria and other microorganisms actually live in an aqueous environment - the thin film of water on and within substrate particles. Thus, there is an optimal moisture range in aerobic cornposting of 50-70% of dry weight (Curtis et *al.* 1991). Too much moisture will lead to anaerobic conditions within the solids and too little will inhibit microbial metabolism and growth.

If saturated conditions are being maintained in the compost cover layer, then anaerobic bacteria will be favoured and anaerobic decomposition will occur.

Nutrient Balance

Microorganisms need sufficient quantities and balance of many nutrients for growth and reproduction. In MSW compost there is usually no lack of essential nutrients. However, if there is an abundance of carbon compounds but little nitrogen (i.e. C/N ratio > 25), bacteria will have a lot of organic substrate for metabolism but may find nitrogen to be the limiting factor for growth. The addition of sewage sludge, manure or other nitrogen-rich material is often used to decrease the C/N ratio of MSW compost (e.g. Bell *et al.* 1972). Wood wastes, straw and some leaves are very high C/N and if composted with MSW, perhaps as bulking agents, the rate of decomposition may be reduced.

In the current compost layer models (Fig. 5), the use of wood waste compost or addition of wood wastes to MSW compost might prove to be an effective way to decrease the rate of compost degradation and increase longevity of the oxygen barrier.

3.4 Physical Nature of MSW Compost

The physical characteristics of compost have received much less study than the soils to which it is added as an amendment (Gallardo-Lara & Nogaies 1987). Compost is low in bulk density and high in porosity, so that when it is added to soil in large amounts, water penetration and retention, air permeability and pore size distribution are increased. From a plant growth perspective, porosity is improved. Increase in soil water holding capacity is attributed to greater porosity and the colloidal nature of compost which makes the soil particles more hydrophilic.

The bulk density of compost increases as it cures. Yhland & Karlsson (1971) estimated that density increases by at least 30% in windrow cornposting. The final dry matter density was about 550 kg m^{-3}, about double the density of raw household refuse. They noted that if MSW is compacted in a landfill, decomposition will be minimal (e.g. a closed landfill can be developed for parkland), although a small amount of methane gas will be created.

The presence of other materials can dramatically change the physical properties of MSW compost. Composting systems which do not remove inert constituents will produce composts rich in plastics, glass and non-ferrous metals. Other materials, such as manure, sewage sludge, sawdust or food processing wastes may be added to compost specifically to change its textural or density characteristics. For example, raw compost can handle up to one-third its weight in sewage sludge (typically 40% water) without seepage outflow (de Haan 1981).

3.5 Chemical Nature of MSW Compost

Much of compost literature refers to the use of compost in agriculture and horticulture as a soil amendment, for fertilization or to improve soil physical properties (Johnston et *al.* 1989). Our interest in compost is not as a plant growth medium or agricultural product, but we must be conscious of the possible biotoxic and physiological effects of compost constituents on organisms or in the environment.

Generally, MSW composts begin as a very complex, heterogenous mixture of organic and inorganic compounds with major components of cellulose, lignins, fats, tannins and inert materials (Gonzalez-Vila & Martin 1985). Organic matter typically composes 40% of the wet weight and about half of this is lost during compost production (Yhland & Karlsson 1971). The composting process degrades the organic matter into a relatively-stable, humus-like product in which humic acid represents about 3 to 6% of the organic matter. The processes of decomposition and immobilization are both at work. The structure of the humic compounds and the combination of other organic chemicals will vary with the type of feedstock and this places different demands on the decomposing microorganisms.

The City of Guelph has undertaken a pilot study of MSW compost quality involving a comparison of the "two-stream" and "three-stream" collection methods. The composition of incoming raw organic material from both streams and in the finished compost is shown in Table 6. There is very little difference in the quality of the two-stream and three-steam organic fractions. This may be a result of the nature of the study (i.e. small pilot project), which has excellent cooperation from its household participants (Gibson 1991). In the finished compost higher levels of light and heavy metals are present, although all those tested were well below the Ontario guidelines (OMOE 1991). The PCB contents of incoming and finished materials were not reported. In contrast, Golueke and Diat (1991) reported that source separated organics had 2 to 5 times lower concentrations of heavy metals than organics separated at a central processing point.

Table 6. Composition of the two- and three-steam incoming organic fractions and the finished compost for the Guelph cornposting pilot study (from Gibson 1991).

Constituent	Two-Stream	Three-Stream	Finished Compost
pH	5.3	5.2	7.3
% dry matter	45.5	48.2	54.6
% c	45.5	45.9	28.3
% N	2.0	2.2	1.5
% P	0.3	0.3	0.3
% K	1.1	1 .o	0.9
% Ca	2.6	2.7	6.4
% Mg	0.4	0.4	1.7
Zn (mg/kg)	46.7	44.6	135.6
Mn (mg/kg)	100.0	92.0	266.5
Cu (mg/kg)	10.8	12.9	22.8
Ni (mg/kg)	1.8	1.6	6.8
Co (mg/kg)	0.3	0.2	2.0
Cd (mg/kg)	0.3	0.3	0.6
Cr (mg/kg)	4.1	4.1	8.1
Pb (mg/kg)	7.7	7.1	37.5

3.5.1 Compost Maturity

The use of immature MSW compost in agriculture has received a lot of study (Jimenez & Garcia 1989, Inbar *et al.* 1990, Riffaldi et *al.* 1992). The rapid decomposition of fresh compost may cause a decrease in oxygen for plant roots and may create an anaerobic, strongly-reducing environment (Jimenet & Garcia 1989). Compost with too high a C/N ratio will immobilize nitrogen in the soil and ammonia released by certain types of decomposition may be toxic to plants. Toxic products (e.g. heavy metals, acetic, propionic and butyric acids) in immature compost have also been shown to inhibit seed germination and other plant physiological processes, which are sometimes used as bioassays of compost maturity (Garcia *et al.* 1990).

Cornposting reveals a more or less sequential evolution of microorganisms as the substrates and physical and chemical environment changes (Gallardo-Lara & Nogales 1987). Bacterial populations peak quickly but then decline more slowly, while fungal populations increase progressively with time and with dosage. Actinomycete bacteria appear and become important only when the compost becomes mature and dries out.

Characterization of compost maturity has proven to be difficult to standardize (Inbar et *al.* 1990, Riffaldi et *al.* 1992). Inbar *et al.* (1990) advocate that a combination of several parameters be employed to quantify the changes taking place during maturation. Methods include chemical analyses, physical analyses, microbial assays, plant bioassays, spectroscopy and degree of humification. No single measurement is relevant to all the important processes controlling decomposition.

The C/N ratio may be high initially (i.e. above 30) and produce a deficiency of available nitrogen due to the accelerated growth of compost microorganisms that use nitrogen for their own development. C/N ratios of mature compost vary widely from 5 to 20, thus the C/N ratio cannot be used as an absolute indicator of compost maturity, but cation exchange capacity is useful (Harada & Inoko 1980). Mature compost brings about higher concentrations of NO, in soil but lower amounts of total nitrogen than poorly developed compost. About 35% of raw sewage sludge nitrogen is lost in cornposting (Zibilske 1987).

Microbial reactions in the compost may cause the formation, of organic acids, especially isovaleric acid, valeric acid and isobutyric acid, which temporarily increase the acidity and may form complexes with metals. Compost can retain large quantities of natural phenols in solution for over one year and increases in polycyclic aromatic hydrocarbons may be detrimental to some plants (Gallardo-Lara & Nogales 1987). Phenols and other aromatic compounds released from compost into tailings may be beneficial in the bacterial reductive dissolution of Fe(III) oxides (LaKind & Stone 1989, Lonergan & Lovley 1990) but they may be harmful if released into the environment (Vaughn et *al. 1984).*

3.5.2 Acidity

Mature compost tends to be neutral or slightly alkaline with a strong buffering capacity. When compost is combined with acid soils, the acidity is found to decrease in proportion to amount of compost added (Gallardo-Lara & Nogales 1987).

Yhland & Karlsson (197 1) found a wide range of pH values in. windrow compost, which centred around neutral. Oxygen-deficient conditions at the bottom of the pile were generally acidic at first then moved toward neutral pH. Leachate from the bottom of the pile reflected these conditions. They concluded that the pH was the result of the particular decomposition processes occurring in each treatment and sample location in the pile.

3.5.3 Hazardous Chemicals

Even mature compost may have toxic levels of some pesticide residues. Kovacic et al. (1992) report that only 28% of 2,4-D herbicide was degraded in 28 days of simulated aerobic cornposting. They conclude that the normal composting temperature of 65°C is inadequate to destroy many pesticides. Pesticides and herbicides could then be reapplied to crops in compost in a largely uncontrolled manner.

Some phenoxy herbicides in landfill leachates have proven to be much more resistant to microbial degradation than the bulk of the carbon compounds (Racke & Frink 1989). Gintautas et *al.* (19921 suggest that these herbicides represent the disposal of only a small quantity of household hazardous waste and could pose a threat to the groundwater.

Golueke and Diaz (1989) reviewed the use of composting and other techniques for the disposal of hazardous wastes. They concluded that the ability of biological systems to break down toxic compounds was being underestimated and that, with proper measures, microbes would actually do a faster and cheaper job than most thermal or chemical systems. Some researchers of anaerobic cornposting believe that pathogen kill is just as significant as in aerobic composting but may take longer (Logsdon 1990).

The fate of hazardous chemicals in the compost layer on tailings will be hard to predict and may be understood only with field trials. These types of compounds must be monitored in experimental tailings and compost leachates to ensure that the use of large amounts of high quality MSW compost does not constitute a significant new source of hazardous chemicals in the environment. However, ‘it is clear that MSW compost with high initial levels of hazardous chemicals will be unlikely to get public approval for export to, and use on, tailings areas.

3.5.4 Heavy Metals and Micronutrients

Municipal composts may carry high levels of some trace metals (e.g. Pb, Zn, and Cu) and they may increase the total and extractable levels in soils to which they are applied. However, the availability of these metals to plants is low, since only some heavy metals seem to be absorbed by plants in significant quantity, especially cadmium and mercury and to a lesser extent arsenic and lead (Gallardo-Lara & Nogales 1987). Metals tend to be retained by soil organic matter unless they are in the form of soluble salts or are exposed to acidic conditions (Kirkham 1977). Repeated application of compost and sludge to crops did not result in proportional increases in heavy metal concentration in either forage or grain (Giordano et *al.* 1975). However, in the case of cadmium, Keller & Brunner (1983) calculated that in 14 years, the continuous use of compost will have enriched Swiss soils to such an extent that their cadmium content will prevent the production of food for human consumption.

Chaney (1990b) modelled Cd intake in a western diet over a lifetime and concluded that the worst case situation (i.e. lettuce and spinach grown in sewage sludge-amended garden soil) would not produce a health effect because of Cd immobilization by adsorption to organic matter and the presence of sufficient Zn to interfere with absorption in the human intestine. He noted that Cd in anoxic rice paddies is in the form of CdS, an insoluble compound. He has criticized the procedure and rationale for U.S. EPA standards for heavy metals in sludge since they are not based on bioavailability (see section 4.3).

Leaching and plant uptake of Cd, Cr, Ni and Zn were studied by Dudka & Chlopecka (1990) in sludge-amended soil. Chromium was associated with organic matter and Cd, Zn and Ni were tied up with Fe-Mn oxides. The amount of all metals in the leachate increased with large sludge dosages, but only Ni and Zn were absorbed by rye grass in significant quantities.

Compost at high doses may produce undesirable effects through toxic levels of boron or heavy metals. This is mainly a result of industrial wastes or wastewater but problems may also result from consumer products in municipal waste with post-collection separation (i.e. two-stream). Toxicity problems tend to increase with time, with soil pH decrease or in presence of nitrogen or sulphur compounds (Gallardo-Lara & Nogales 1987). Boron becomes very mobile and is toxic to many plants, but is easily leached out of soil. However, on a positive note, some plant micronutrient deficiencies have been solved with compost amendments (de Haan 1981).

Walker and O'Donnell (1991) analyzed MSW compost samples from nine existing facilities. Although heavy metal content was variable, the mean concentrations were low and similar between sites. The only exception was one facility which co-composted 25% sewage sludge with its MSW compost and the higher metal levels reflected the contribution of the sludge (see section 4.3). Most metal concentrations were below the Ontario guideline standards for aerobic compost (OMOE 1991).

The fate of heavy metals in the compost in the tailings cover models is difficult to predict. Since leaching of the compost could be inhibited within a compacted layer, there may not be much leachate leaving the tailings and entering the outside environment.

3.5.5 Pathogens

For use in food crops or near human habitation, compost should be virtually free of pathogens. High quality compost is produced by optimal aerobic decomposition and the development of high temperatures for a "sufficiently long period of time" (Vajdic 1984). But there are some questions and conflicting views about the safety of compost and sewage sludge which is less than high quality or that matures under suboptimal conditions.

Vajdic (1984) suggested that the normal MSW cornposting process may not be entirely successful at removing bacterial and viral pathogens, although their numbers would be greatly reduced. Mixing of compost layers can allow a depressed bacteria group to be redistributed and perhaps multiply in cooler material but adequate process controls should ensure its eventual destruction. She stated that physical factors, such as excessive wetness or compaction causing anoxia, can depress microbial populations. However, removal of the environmental limitation normally results in a prompt recovery of microbial activity (Vajdic 1984). In contrast, Cooper and Golueke (1979) observed that the persistence of many pathogens in sewage sludge, such as bacteria, viruses and parasites, is favoured by low temperature, alkaline pH, high organic matter and high moisture content.

Parasite destruction is an important objective of high temperatures in aerobic compost production. During the cornposting process, coliform bacteria appear in the leachates of MSW and sewage sludge, in parallel to their development in the compost, but are quickly destroyed by the cornposting conditions (Yhland & Karlsson 1971). Parasite eggs were numerous in the sludge but virtually absent from the compost fraction in the Swedish study. They concluded that parasite eggs may be very persistent in leachates unless high temperatures have been present for an extended period in the compost production.

High C/N ratios (e.g. as in sawdust) deprive most microorganisms of the nitrogen they require for fast growth and thus suppress pathogens. However, other microorganisms, acting as secondary pathogens to humans (e.g. *Aspergillus fumigatus*), may be associated with wood and plant wastes and cause mostly respiratory problems. in weakened individuals and workers with frequent exposure (Curtis et *al.* 1991).

The absence of pathogens in the compost used for tailings cover could be ensured by the use of the highest quality (and most expensive) MSW compost. However, it remains to be tested whether the use of immature compost in the proposed cover layer designs (Fig. 5) would allow the survival and spread of pathogens into the environment.

3.5.6 Compost Leachates

The fundamental question in the use of MSW compost on tailings is what compounds and pathogens may leave the tailings impoundment in drainage waters, both from the tailings and from compost leaching. The literature indicates that there is good potential for revegetation on a tailings cover layer. As a result, overburden erosion and runoff in the current models (Fig. 5) should not be a source of problems. The major question about this model appears to be the effect of compost maturity on leachate quality.

Petruzzelli (1989) argues that heavy metal extractability is the important characteristic of waste materials in the ecosystem, not the total amounts of heavy metals in the solid phase. Heavy metal extraction chemistry and techniques have received attention in recent years, for example in studies of aquatic sediments (Tessier et *al.* 1979, Belzile *et al.* 1989). In many studies, however, leachate data is the only measure of what is available and mobile in the system of interest. Several studies give us useful information about potential leachates and the problems they may cause. However, landfill leachates represent a complex, “worst case” system for contamination which should not be compared closely with drainage from mature compost.

Reinhard *et al.* (1984) found that most compounds in landfill leachate originate from decomposition of plant material and include aliphatic and aromatic acids, phenols and terpenes with minor contributions from chlorinated hydrocarbons and nitrogen compounds. Organic acids were found to comprise 11% of the 4450 mg/L alkalinity found at a landfill site (Baedecker & Back 1979). Anaerobic decomposition of refuse also produced the same organic acids, with acetic acid and butyric being the most important volatile leachates (Barlaz *et al.* 1989).

Bolton & Evans (1991) analyzed the elemental composition and speciation of leachates from four southern Ontario municipal landfills. The leachate composition was quite variable but contained high concentrations of many light and heavy metals and other toxic elements such as chloride ions and boron. Soluble cadmium was complexed with humic acid and chloride, and was found to exceed acceptable water quality limits.

Murray & Beck (1990) found that landfill leachates contain a wide variety of synthetic organic chemicals, some of which are classified as hazardous wastes. The cumulative toxic potential of these compounds is unknown and this, they feel, points to the need for more intensive monitoring of landfill leachates.

Incorporation of composts increases the salt content of soil but these levels are immediately reduced by rain water percolation (Gallardo-Lara & Nogales 1987). When raw municipal compost is incorporated into soil, water-soluble components are leached from the refuse by percolating rain water. Composts are sometimes used for their beneficial salts which enrich the levels of potassium, calcium and magnesium in soil.

Yhland & Karlsson (1971) observed that leaching from compost windrows was small and linked to heavy rainfall events. The leaching was primarily due to surface runoff rather than seepage, since the windrow (2-3 m^2 cross-sectional area) had a large moisture capacity which stored most precipitation. A BOD four times higher than for municipal waste water was measured in windrow leachates, but chemical oxygen demand was somewhat lower. Nitrate was present at low concentration and ammonium reflected the quantity of sewage sludge incorporated into the compost and the more anaerobic conditions at the bottom of the pile. There was very little leaching of phosphorus even though large amounts were present in the compost. They concluded that surface water and drainage leachate from windrow compost piles had a composition roughly the same quality as municipal waste water before treatment.

Analyses of some toxic compounds from the study of Yhland & Karlsson (1971) are presented in Table 7. It is evident that relatively little of these toxic compounds escapes from the windrow compost pile in leachates, even when they are in high concentration in the solid phases. Elemental analyses of MSW compost, sewage sludge and windrow leachates (Table 8) show the same pattern for most constituents. There is good correspondence between the leachate concentrations and the concentrations in the liquid fraction of the sludge (i.e. Table 8, rows 2 & 5).

Table 7. Median concentrations of toxic compounds in MSW compost, sewage sludge and leachate fractions of windrow compost (Yhland & Karlsson 1971 I.

Fraction	DDT ug/kg	PC0 ug/kg	fluoride mg/L	Cyanide ug/L
compost	220	900	31.5	1
sludge	4.2	4.3	5.4	3.3
leachate	.085	.12	.6	2.1

Yhland & Karlsson (1971) observed that the supply of basic elements is dominated by the compost fraction (i.e. greater than 96%), even though the samples contained a 50:50 wet weight mixture of compost and sludge (1.7% dry matter). Their attempt to compare compost leachate composition with leachate from a municipal landfill with uncured refuse was ambiguous because the bulk of the landfill material was dry and thus not being leached.

The literature on leachates suggests that the export of organic and inorganic chemicals from the compost cover layer (Fig. 5) will not be a problem, even if rainwater does infiltrate the overburden layer and percolate through part of the compost layer. The problem period would likely be only in the early stages of decomposition, if immature compost was used, or in the spring, when water tables are high. Experimental investigations would be necessary to test this hypothesis.

Table 8. Presence of basic elements in the MSW compost, sewage sludge and leachate fractions (median and average values) (Yhland & Karlsson 1971).

Material Studied	No. of recording	Basic Elements ppm												
		Cd	Cu	Zn	Pb	Ni	Co	Mn	Fe	V	Mo	Cr	Hg 1)	As
Compost material, dried, median value	appr. 70	3.5	180	900	250	10	<20	600	1.25%	<30	<20	60	5.0	<100
Leachate, liquid phase median value	SO-60	0.01	0.4:	<3	0.21	0.10	CD.05	3	8	co.10	<0.10	<0.05	0.01	
Leachate, DM median value 2)	8	13	500	000	350	30	<50	3400	1.4%	<10	<50	100		<250
Sewage sludge, liquid phase, average value	5	co.03	0.4	<3	0.1	<0.06	<0.06	0.09	10	co.1	a.05	<0,05		
Saltsjöbaden, median value		<0.01	0.3(	<3	0.1(	<0.05	<0.05	0.10	10	co.1	0.05	a.05	0.2	
Sewage sludge, DM average value 3)	5	6	570	300	150	30	<20	280	2%	<30	<20	50		
Saltsjöbaden, median value		5	550	200	150	20	<20	300	2.1%	<30	Q O	50		<.00
Sewage sludge, DM Uppsala, average value		11	960	890	293	88	12.2	373	•	•	7.4	176	12.(	6.6
Sewage sludge, DM Åkeshov, average value	unknown	33	840	780	440	100	43	300	2.4%	•	•	300	12	

1) Analysis undertaken on mixed samples. No. of recordings 31, 12, & 3 respectively

2) Median value of dry content = 0.43 %

3) Dry content median value, 1.7 %; average value 1.0 %

3.5.7 Odours, Methane and Other Gases

Yhland & Karlsson (1971) reported that the production of objectionable odours was not a problem in their windrow composting. They analyzed several gases emitted during the first three months of decomposition by a pile composed of milled household refuse mixed with sewage sludge (Table 9).

Table 9. (a) Gas composition of air samples taken from the interior of a compost-sewage sludge windrow over 30 days (Yhland & Karlsson 1971).

Age of Windrow: Days	O_2 %	CO_2 %	CO %	CH_4 %	C_3H_6 %	C_3H_8 + C_4H_{10} %	C_2H_4 %	NO %	NO_2 %
2	5.2	14.7	0.03	0.06	<0.001	<0.001	<0.01	0.0002	a.0001
14	0.2	22.5	0,004	0.5	<0.001	<0.001	43.01	<0.0001	<0.0001
30	1.0	24.6	0.001	0.9	<0.001	<0.001	<0.01	4.0001	<0.0001

Table 9. (b) Air sample taken at 2 months, pile temperature 52°C (Yhland & Karlsson 1971).

CO_2 %	CO %	CH_4 %	NO + NO_2 %	Water Vapour g/l
15	0	detected	0.5	5

The table shows that O_2 decreased while CO, and CH, increased as expected during the rapid initial decomposition period. Values for hydrocarbons and nitrogen oxides remained low. At two months, CO, and CH, have decreased and nitrogen oxides were significantly higher, indicating that denitrifying bacteria were active. In the nearby landfill, larger quantities of methane were produced along with some ethylene and hydrogen sulphide (data not shown).

Methane is produced by methanogenic bacteria, such as *Methanobacterium*, which reduce the CO, previously produced by aerobic decomposers. Some aerobic bacteria, such as *Pseudomonas*, can oxidize CH, in respiration in the oxygenated upper layers of the compost, but an excess of methane can be injurious to plants or even be explosive (Flower et *al.* 1978). Small amounts of several gases (CH,, H_2S, H,, N_2) may evolve under anaerobic conditions, usually when moisture content and pH are high. In quantity, many of these gases are phytotoxic, as is CO,. Gallardo-Lara & Nogales (1987) observed that compost added to soil could enhance production of ethylene gas, which suppresses plant pathogens and stimulates a variety of plant hormonal responses.

The slow aerobic and anaerobic decomposition processes expected in the compost cover layer models (Fig. 5) should not release significant quantities of gas or odours into the environment. Gas evolution can be monitored during laboratory experimental work to predict the likelihood of a problem in the field.

3.6 Summary

In the design of compost cover layer for tailings, we are trying to produce anoxic conditions and anaerobic processes that would cause problems in aerobic compost production. However, a layer of MSW compost designed to stop AMD must not also release potentially detrimental substances into the environment.

There are attractive benefits to using uncured (immature) MSW compost as a tailings cover:

a) diversion to tailings use would reduce the input to the MSW compost stream and thus be cheaper to produce,

b) an engineered compost cover on tailings might not have to meet as stringent contaminant specifications as required for agriculture or horticulture grade compost,

c) the higher BOD of immature compost and other chemical characteristics may be more beneficial than mature compost in its use in creating reducing conditions in the tailings.

The importance of quality in MSW compost must be examined in the laboratory and in field tests to determine the environmental risk of the use of different qualities of compost on tailings. There might not be sufficient quality control at the municipal level on the sources of raw MSW organic matter in order to eliminate toxic compounds from immature compost or even mature compost. Alternatively, degradative and complexation processes within the compost layer could render toxic or volatile compounds and pathogens harmless before they could reach the environment. Or if drainage from the compost-tailings system is largely suppressed, then-the quality of the compost leachate may not be an issue.

The use of other waste materials, such as wood wastes, may add beneficial characteristics to a MSW compost, especially in suppressing decomposition processes. However, leachates from other types of wastes must also be examined for possible detrimental effects in the environment. Odours are a common downwind problem with outdoor placement of compost and sludges and this also must be assessed for the compost cover layer designs and types of waste that could be employed.

4. CO-COMPOSTING OF MSW COMPOST AND SEWAGE SLUDGE

Municipal sewage sludge and its compost form are plentiful waste products that have sometimes been used to great benefit as an agricultural soil amendment. It should be considered as a potential co-composting component of MSW compost in the tailings cover layer design. But the use of sewage sludge may bring some problems along with the benefits.

4.1 The Nature of Sewage Sludge

Sewage sludge is the complex mixture formed by anaerobic treatment of municipal waste water. It is made up of a labile fraction composed of easily-degradable carbohydrates, soluble organic matter and proteins. The stable fraction, which can make up 30 to 80% of municipal sludge, contains recalcitrant components, such as microbial cell walls, lignin-cellulose polymers and organic-inorganic complexes (Boyle 1990).

Three different approaches are used to dispose of sewage sludge: anaerobic digestion, aerobic composting and land treatment. Over 75% of the labile fraction and much of the stable fraction may be digested anaerobically. Composting of de-watered sludge decreases odours, pathogens, volume and moisture while causing humification of organic matter, much the same as in MSW windrow cornposting. Land treatment of sludge depends on degradation of various constituents in the heterogenous microhabitats and fluctuating redox conditions of the soil, but it appears to work very well (Boyle 1990, Brockway 1988).

4.2 Benefits

A large amount of literature exists on the benefits of sewage sludge as a soil amendment and on the usefulness of soil decomposition as a way to dispose of sewage sludge (Boyle 1990). In most cases sludge or sludge compost has been a success as a low-grade fertilizer and soil conditioner, primarily by increasing soil organic matter (Reed et al. 1991). Hinesly et al. (1982) found that, while sewage sludge increased heavy metal concentrations and acidity in strip-mining spoil, the added elements (except for Ni) were less available for plant uptake than in the spoil alone. These results agree with the results reviewed by Kirkham (1977) on the beneficial retention of heavy metals by sludge organic matter.

The co-composting of sewage sludge and MSW compost often produces a better quality compost due to higher microbial nutrient values in sewage sludge, especially with respect to nitrogen and C/N ratio (Naylor *et al.* 1990). For use as plant fertilizers, however, organic matter co-composted sewage sludge is often seen to immobilize nitrogen causing an increased nitrogen fertilizer requirement (Sims 1990).

Sewage sludge appears to offer the same potential benefits as MSW compost as an oxygen-consuming layer on tailings (section 1.2) and as a source of ameliorative chemicals and decreased acidity (section 1.3). Sewage sludge added to quarry water successfully neutralized acidity and caused the precipitation of metals, primarily through the action of sulphate-reducing bacteria (Davison et *al.* 1989). No hydrogen sulphide gas was noticed and the system re-acidified after two years due to depletion of sludge. Addition of 5% sawdust to sewage sludge substantially reduced the concentrations of nitrate in leachate from a sludge-pyrite spoil layer (Urie et *al.* 1982). Seaker (1991), in a 12 year study of reclamation of coal mine spoil, found that metals were retained mostly in the sludge plough layer. Percolate water and ground water quality were unaffected by the rate of sewage sludge application and there was no evidence of bioaccumulation of metals, even when they were applied at higher than agricultural rates.

Ferric iron (Fe^{3+}), under certain conditions, is an important oxidizing and solubilizing agent of pyrite (Equation 4). When complex organic material such as sewage sludge is added to pyritic tailings it is highly reactive and plays a significant role in metal complexation. Pitchel et *al.* (1989) found that a water-soluble organic component of sewage sludge functioned as the ligand in Fe^{2+} oxidation. The reactive functional Qroups were revealed to be carboxylic acids, polysaccharides and amine groups. The Fe^{3+} produced was immediately complexed with organic matter, rendering it inactive in the formation of acid from pyrite (i.e. the indirect oxidation process), although still very mobile. Dean et *al.* (1974) found that a two inch layer of sludge or compost buried 7-13 cm under the surface of tailings prevented or retarded oxidation of sulphides, although it is unclear how this was measured.

4.3 Risks

Sewage sludge is not viewed by society as a renewable resource and, consequently, is not kept separate from toxic organic chemicals and heavy metals present in industrial wastes that enter municipal wastewater (Boyle 1990). Sludge is less than 1 % of the total flow through a sewage treatment plant but typically contains between 50% and 80% of the Cd, Cu, Pb and other metals flowing' in (Lake et *al.* 1989). Most metals (90%) are associated with or bonded to the solid phase rather than being soluble. Raw sludge is a less stable form than activated or digested sludge and cadmium is the least stable metal.

When used by itself, liquid sludge (3-8% solids) is sprayed on agricultural or forest soil. The rate of application to a particular soil system is dependent on its capacity to handle the most negative aspect of sludge composition or activity (Boyle 1990, Brockway 1988). Uppermost, is the necessity that humans do not acquire pathogens from recently applied Sludge. Most sludge sites have an upper limit on the rate of application due to buildup of toxic elements or compounds by storage in the soil, in the ground water or by bioaccumulation in the food web. There is only minor accumulation of the heavy metals Cd, Cr and Ni in herbivores in the upland forest site in Michigan, along with enhancement of their forage quality (Brockway 1988).

Public concerns about sewage sludge involve pathogens, bioavailability of heavy metals, odours, toxic organics and methane production (Boyle 1990). Brockway (1988) found that the public was interested in, and supportive of, the disposal of Sludge on relatively inaccessible forest lands. But it is clear (Golueke 1983), that the pathogenic content of raw sludge is so great that, if applied to developed land, it would pose a hazard to public health. He argues that additional processes exist, such as composting or in natural soil conditions, which can inactivate even the most hardy pathogen.

Chaney (1990a,b) reviewed twenty years of research on the use of sewage Sludge. He attacked the U.S. EPA standards process and regulations for sludge as being too stringent, simplistic and unrealistic in the light of considerable research on how sludge can be safely used. He argues that there is a "no observed effect level" for the use of quality sludge because there are mechanisms of adsorption for metals and organic chemicals in the sludge which immobilize these toxic compounds. He introduced the idea of a "soil-plant barrier" which limits the movement of toxic substances into the food chain. This is key part of his concept of "environmental toxicology" which attempts to "holistically and realistically" assesses the bioavailability of a substance which is present in the sludge. (The major problem being direct ingestion by cattle Of sludge sprayed on leaves.) Too often, he maintains, standards have been set based on an unrealistic, worst-case experiment, which bears no relation to the real world. He points out that the proposed EPA regulation does not presently have pH control requirements on sludge use regulations when pH is the most important single factor to control metal transfer and toxicity (Chaney 1990b).

Even so, there is a higher risk associated with using sludge co-composted materials due to generally poorer quality control possible with sewage sludge, chiefly because of industrial heavy metal and hazardous waste content. The quality of sludge employed in agriculture must be constantly monitored to ensure compliance with government regulations (Reed et a/. 1991). Incorporation of sewage sludge with composts increases the salt content of soil, although concentrations are immediately reduced by rain water percolation (Gallardo-Lara & Nogales 1987).

Barlat et *al.* (1989) found that leachates from samples of MSW-sewage sludge and BOD were similar to those from landfills. Na, P and Fe decreased with compost age, whereas Cr, Ni and Zn increased initially; then declined also. A major portion of metals was lost due to anaerobic processes in lysimeters. This result is consistent with the concerns about metal mobilization expressed by Ribet et *al.* (1991).

The mobilization of heavy metals, organic chemicals, salts and pathogens is a concern if sewage sludge is used in the compost cover implementation. Composted sewage sludge appears to offer much less risk than raw sludge but is unclear what advantages it may offer as an amendment for the compost layer. Estimates by Molot (1992) of the availability of sewage sludge in Ontario show that it could provide only about 5% of the volume that is available with MSW compost.

4.4 Summary

Composted sewage sludge appears to offer the same benefits as MSW compost as an oxygen-consuming barrier. Sludge compost would likely be co-composted with MSW compost. There is evidence that sludge will also be of benefit by binding to ferric iron rendering it inactive in pyrite oxidation. However, potential risks concerning heavy metals, organic chemicals and pathogens in sludge must be investigated. It may be found with experimental work that the compacted compost layer design suppresses odours and prevents the release into the environment of these hazardous substances.

5. INDUSTRIAL SOURCES OF ORGANIC WASTE

Municipal compost may not available in sufficient quantity to meet the needs of tailings reclamation. Other major sources of organic waste such as lumber mill waste, paper mill sludge and peat may be satisfactory substitutes or co-composting materials to use with MSW compost in a tailings cover layer.

5.1 Forest Industry Waste

Much of the current forest industry waste is sawdust, stripped bark and wood trash, which used to be burned, but are now found in unsightly, dusty piles (Bell et al. 1972). Since the mining and forestry areas of Canada greatly overlap, a joint solution to this major lumber industry problem and the mine tailings reclamation problem seems appropriate.

Lumber wastes have long been advocated as a source of needed organic matter in the reclamation of mine tailings (Watkin & Winch 1973, Sutton & Dick 1987). Tuttle et *al.* (1969) noted how sawmill tailings formed a dam which backed up a stream polluted with acid mine drainage. Acidic water seeping through the decaying organic matter was higher in pH and created a black metal sulphide precipitate on the downstream side. He obtained cultures of *Desulphovibrio* bacteria from within the organic layers, which were responsible for producing the sulphide ions which precipitated the metal.

Lumber waste has had mixed success as a plant growth medium because of the presence of a high C/N ratio, phenolic compounds such as tannins, certain carbohydrates, many aromatic organic chemicals and acidic decomposition products which can be toxic to some plants (Davey 1953, Bell *et al.* 1972, Solbraa *et al.* 1983). The application of fresh lignaceous material to soil can lead to phytotoxic effects and nitrogen immobilization (Zucconi *et al.* 1984).

However, lumber waste can be improved by windrow cornposting with the addition of a suitable nitrogen source (Bell *et al.* 1972). After sufficiently long cornposting, wood wastes mixed with cattle manure (2:1 ratio) will produce a humified product that has good quality for agricultural use (N'Dayegamiye & Isfan 19911. The chemical composition of the materials they used is given in Table 10.

Table 10. Chemical composition of wood shavings, sawdust, peat moss and cattle manure before cornposting (N'Dayegamiye & Isfan 1991).

Material	pH	Organic C %	Total N %	C/N
wood shavings	5.5	50.6	0.68	74.4
sawdust	5.3	55.2	0.40	138.0
peat moss	4.8	48.9	0.90	54.3
manure	6.7	9.7	0.49	19.8

The pH and nitrate increased during composting for all samples while C/N ratio decreased. Ground wood shavings out-performed sawdust and partly-decomposed peat moss in cornposting rate, pH, C/N ratio and as a growth medium for faba beans and corn, although all composts trials benefited from nitrogen fertilization. Decomposition is also aided by inoculation with cellulytic fungi (Cline & Chong 1991).

Wood wastes may have a direct benefit in the chemical amelioration of oxidized tailings. The type of decomposing organic matter and its oxidation products may lead to very specific chemical interactions. Vaughn et *al.* (1984) used a variety of softwood and hardwood wastes to remove ferrous iron from the drainage water in peaty soils and acidic soils. They concluded that water-insoluble tannins in the conifer bark immobilized the Fe(II) and avoided the use of toxic phenolic compounds for mitigation of Fe(II) oxidation.

It seems likely that lumber wastes can be employed beneficially in an oxygen barrier cover on tailings. It is not known whether raw wood wastes will produce satisfactory decomposition products and leachates or whether composting will be necessary or advantageous before these wastes could be employed. Conifer barks were found to compost much faster than hardwood bark, possibly because of higher levels of nitrogen compounds (Solbraa et *al.* 1983). Plant growth inhibitory substances were reduced to non-toxic levels in about two weeks of composting.

5.2 Food Processing Industry Waste

There is relatively little in the literature about the composting of food processing industry wastes (Bellamy 1991). In some parts of North America these wastes constitute a big disposal problem and, because of a lack of incentives, much of the waste ends up in inexpensive landfills (Bellamy 1991). Florida, a progressive waste management jurisdiction, recycles its considerable citrus and sugar cane pulp wastes as animal feed (Smith 1990). Goldstein (1992) reported that wastes from U.S. food preparation sources, such as produce warehouses, fresh food processors, grocery stores and restaurants, constitute 6.6 million tons annually and cost over $500 million for disposal. The agricultural regions of southern Ontario may provide opportunities for seasonal compost. Most food processing wastes are considered a clean source of organic matter, although pesticide residues may be a factor in the quality of some feedstocks and meat wastes often have obnoxious odour problems (Bellamy 1991).

5.3 Other Organic Wastes

Paper Mill Sludge

Ontario produces 2000 tonnes of paper mill sludge per day. No toxic effects are seen in the use of paper mill sludge compost in horticultural applications, but significant amounts of nitrogen fertilizer must be added to overcome the high C/N ratio Kline & Chong 1991). Vogel and Rothwell (1988) found that paper mill sludge was a useful additive to mushroom compost in the reclamation of acid coal mine spoils. Their analyses of these two organic materials (Table 1 1) shows that high levels of calcium in the sludge helped neutralize the acidic nature of the compost.

Heavy metals analysis of paper mill sludge and other soil amendments showed that the sludge compared favourably with manures and top soil for Cd, Cr, Cu. Pb, Ni, Zn and Hg. All concentrations were well below the state of Maine maximum concentrations for food crop soils (Pepin & Coleman 1983). The main components of the sludge were 50% organics (cellulose, microorganisms, lignin and wood extracts) and inorganics (lime, clay, calcium carbonate, titanium dioxide, trace elements).

A paper mill sludge and ash mixture is used extensively on agricultural land in Maine (Pepin & Coleman

1983). Soils amended with sludge suffer from immobilization of nitrogen and mineralization of carbon in proportion to the amount of sludge applied (Zibilske 1987).

In compost cover layer materials with a moderate C/N ratio (i.e. 20 to 30), the addition of paper mill sludge should raise the C/N ratio and slow the rate of decomposition by depressing bacterial activity.

Table 11. Some properties of paper mill sludge and mushroom compost used to amend acid mine spoils (Vogel & Rothwell 1988).

Property	Paper Mill Sludge	Mushroom Compost
pH	7.6	6.8
N %	1.06	2.64
P (ppm)	1,825	7,148
K (ppm)	2,575	19,352
Ca (ppm)	197,897	66,857
Mg (ppm)	5,798	14,823
Fe (ppm)	-4,425	6,183
Al (ppm)	23,026	5,273

Peat

The potential of peat as a self-sustaining oxygen barrier on tailings has been suggested (Reardon & Moddle 1985, Brown 1991, Winterhaider 1992). Winterhalder (1992) has had success in transplanting bog sods to tailings but noted that peat will ameliorate AMD better on fresh sulphide tailings than on oxidized ones. Brown (1991) suggested pumping of peat in a slurry from bogs to nearby tailings areas to establish a new bog as an oxygen barrier. Brown recommends also, that the tailings peat be amended with cellulosic wastes to enhance methane production and thereby reduce hydraulic conductivity of the peat to the infiltration of oxygenated water. Winterhalder (1992) cautions that the extra cellulosic material would make the peat a less desirable growth medium for the maintenance of bog vegetation. This peat layer approach has not yet been tested and could be successful as a long term tailings abandonment solution only if an adequate moisture level and vegetation survival can be ensured.

Bog peat is an abundant, locally-available source of organic matter in most mining areas of Canada, but the current public focus on wetland conservation may discourage its use (Spencer 1990, Winterhalder 1992). The commercial peat industry may expand in the future and produce a great deal more peat material as organic waste. Northern bogs are currently exploited as a source of peat moss for horticultural use and this industry may be expanding in northern Ontario. The demand for Sphagnum peat as a natural moisture absorbent material (by companies such as Johnson & Johnson) is also seeing a dramatic increase (Vitt 1992). Hillman (1987) has advocated the modification and displacement of a portion of Peat wetlands as part of the strategic plans by Forest Canada to expand economic forest lands. Peat, although slow to form, possibly could be harvested and managed as a renewable resource in the Boreal Forest region.

The use of peat may have distinct advantages as a non-toxic, abundant, locally-available and inexpensive source of organic material to be used by itself or in combination with other wastes as an oxygen barrier (section 2.2.3). Peat may also have ,a role to play in the tailings as medium for iron retention which, in turn, reduces AMD. Henrot & Wieder (1990) found that when AMD was leached through peat columns, half the AMD iron was extracted with organically-bound Fe, becoming saturated at low dosages, while Fe-oxide formation continued to increase linearly. Manganese retention was minimal compared to iron and 99% of this was exchangeable Mn. There was little accumulation of Fe-sulfides in the peat submerged in water for 42 days. Fe-oxides were found to be very stable to dissolution under anaerobic conditions and to flushing with simulated acid rain (pH 3.9). In contrast, Reardon & Moddle (1985) found that a peat layer on top of tailings leached with deionized water did affect acid production, presumably because the peat did not export any compounds to the tailings which reduced the aerobic acidification processes.

These two studies indicate that any ameliorative effects of peat will occur when peat is in close contact with the processes of acid production or acidic pore water. Thus, the use of peat would be more beneficial in cover model B (Pig 5b), where the organic matter is ploughed into the tailings.

5.4 Summary

As with MSW compost, other commercial organic wastes have potential as components in an oxygen barrier cover on tailings. The proximity of forest industry wastes to tailings sites makes them an attractive source of oxygen-consuming organic matter which may also release compounds that would depress acid • producing bacterial activity in the tailings. Food processing wastes and paper mill sludge appear to be materials without serious detrimental impacts on the environment, which may be available in large quantity. Peat, currently harvested from northern bogs for use in the horticultural industry, shows ameliorative properties for AMD and should be considered as a locally-abundant tailings cover material as long as it can be managed as a renewable resource.

6. COMPOST SOLUTION COST ESTIMATES

The practicality of MSW compost and other organic wastes for tailings reclamation depends on economic factors as well as scientific and technical considerations. The cost of employing organic wastes from distant sources on tailings in the north will necessarily include substantial handling and transportation costs. The potential demand by tailings reclamation is huge (Molot 1992), so that availability of MSW compost and other organic matter is also a central question.

6.1 Production Costs and Availability

Molot (1992; Appendix B) did an analysis of the potential availability of MSW compost, if the cities and large regional municipalities across Ontario did full-scale composting. He used conservative assumptions about the capture rate of organic material currently going to landfill and calculated that the "operationally-obtainable" organic waste fraction was only 17% of the total waste stream. Other studies have found considerably higher proportions of organic matter available in the waste streams of other cities (e.g. Gibson 1991, Kennedy 1991).

The total amount of organic material feeding into the compost process annually was estimated by Molot (1992) to be 1.4 million tonnes. Assuming a 50% reduction in weight during composting, a yield of 680,000 tonnes could potentially be produced in Ontario each year.

Cost estimates for MSW composting are quite variable, depending on the technology employed and the economies of scale (Dillon & Cal Recovery Systems 1990). Since the major source in Ontario (53%) would be the Greater Toronto Area, Molot (1992) calculated the production costs for one 75,000 tonne per year Toronto composting plant to be $100 - $126 per tonne. This is less than the current public tipping fee for MSW but about four times as much as the cost of landfill disposal (Stonehouse 1984).

This is quite a high price to pay for only 17% diversion of waste from landfills and it raises the question about the realistic availability of MSW compost within the time frame of interest to the mining industry. A recent review of MSW composting projects and plans in Canada (Spencer 1991) reveals that compost plants will be so expensive to build and operate that many municipalities will proceed cautiously with composting as only one part of their integrated MSW strategy. There is currently only one MSW compost plant in Canada at Chertsey, Quebec (Bourque & LeBlanc 1991) and only about seven projects are underway (Spencer 1991).

Another aspect to be explored is the use of immature or low grade MSW compost, if this material functions well as a compost cover layer for tailings. If immature compost could be diverted at the beginning of MSW composting process, municipalities could save a lot on compost production costs. The toxicity of immature compost would likely be low enough for tailings use, only if the more expensive three stream waste collection system was employed and if households cooperated in keeping hazardous wastes out of the organic stream. As noted in the Introduction, the potential demand by the mining industry. alone, would not be satisfied by all the low or high quality compost that Ontario could produce.

6.2 Transportation Costs

MSW compost is useful to a customer only if it is sold and transported at an affordable price. Molot (1992), assumed that the MSW compost production cost would be borne by the municipalities (i.e. free to the mining companies). He estimated the cost of bulk shipment of MSW compost from Toronto to Elliot Lake mine tailings by train, truck and ship/truck. The winter interruption of transport (and the necessary stockpiling of compost at the compost facility) was not included in the transportation cost. Assumptions were made about vehicle capacity, bulk density of loaded compost and the nature of the loading/unloading services. The full cost per tonne of compost for each mode of transportation was: $45 by rail, $46 by truck and $30 by ship/truck. This is still a substantial cost and traffic load, considering the volume of compost that would have to be moved almost 600 km.

However, if no other markets exist for MSW compost or if the costs of producing high quality compost are too high, then it may be opportune to consider the diversion of low grade compost to the reclamation of mine tailings. The cost to the municipalities of shipping low grade compost may be much lower than any other disposal solution.

6.3 Implementation Costs

The implementation costs are difficult to estimate since the depth of compost to be placed on the tailings and the cover layer design (Fig. 5) remain *to* be determined based on experimental work. The minimum thickness of a cover layer that can reasonably be manipulated by heavy equipment would be about one metre. The more complex and thick the layers, the more costly is the solution. However, if a particular cover layer design appears to be a permanent abandonment solution which avoids perpetual AMD treatment, it may be worth a large capital expenditure.

6.4 Monitoring and Maintenance Costs

Monitoring of the tailings impoundment leachate water quality would continue as it does today until closeout at an annual cost of approximately $20,000 - $50,000 per year per monitoring point, depending on how remote its location. Additional sampling and analysis of the compost cover layer and tailings is expected to cost $1,000 - $2,000 per year until closeout. After closeout the costs may decrease to $500 - $1,000 per year.

6.5 Summary

The question of availability of MSW compost in sufficient quantities for use in tailings reclamation is a serious concern as municipalities are only now developing their composting capabilities. Even if MSW compost is given away free to mining companies, handling and transportation to the majority of tailings sites in northern Ontario from sources in southern Ontario will be a major economic consideration. These drawbacks to the use of MSW compost may make northern sources of organic materials more attractive.

7. SOCIAL, ECONOMIC AND ENVIRONMENTAL ISSUES

There are many interested parties involved in the production and use of MSW compost. Governments, with responsibility for the health of people and the environment, regulate general quality aspects of compost production. Community concerns may enter into specific implementations of compost production and use. Market forces and costs may dictate whether a mining company can implement a sound technical and environmentally-acceptable solution.

7.1 Provincial Government Interests

Ontario is experiencing a garbage crisis, with half of its 1400 active disposal sites scheduled to be closed by 1995, the problem being most acute in the Greater Toronto Area (Hanson 1991). The current government is taking an aggressive approach to garbage volume with a stated policy that landfill usage must be reduced by 25% in 1992 and by 50% in the year 2000. The Ontario Ministry of the Environment (OMOE) commissioned an extensive study of waste composition in the province (Gore and Storrie & Decima Research 1991), to compile data to support this' reduction effort. A comprehensive review of the literature on aerobic composting was also commissioned (Dillon & Cal Recovery Systems 1990).

A combination of legislative and cooperative measures is already being implemented in Ontario to solve the "disposal gap" (Hanson 1991). There is a four-fold government approach: (1) Aim at the most abundant wastes; (2) Deal first with the largest sources; (3) Act at key points in the waste management systems; (4) Accelerate existing trends. However, the situation is exacerbated by several recent ministerial decisions: to place a moratorium on the construction of incinerators and close down existing ones that lack proper emission controls; to not pursue a refuse-derived energy program; to prohibit export of wastes outside the jurisdiction in which they are generated.

A major thrust of government policy has been the introduction of a household recycling ("blue box" and "3-R's") program with the highest per capita level of funding in North America. The program is voluntary at the municipality and citizen level, but it has already succeeded in diverting 300,000 tons of material per year from landfills (Hanson 1991). By 1993, 90% of homes are expected to participate, which indicates that public acceptance of recycling is very high and many innovations are being created at the local level.

A substantial amount of money is also being spent on home composting programs, tire recycling and industrial waste diversion. Industry has formed a planning and implementation group to work with its members to address waste disposal legislation, new technologies and changing markets for their products. The Ontario Multi-Material Recycling Inc. (OMMRI) consists of six corporate sectors: the soft drink industry, the Packaging Association of Canada, the plastics industry, newspapers, grocery products manufacturers and grocery distributors.

Cornposting is receiving a lot of attention through initiatives by the Recycling Council of Ontario and the OMOE (cf. Dillon 1990). In April 1991, OMOE released a draft of "Guidelines for the Production and Use of Aerobic Compost in Ontario" (Appendix C). The guidelines treat compost as a product rather than a waste and establish strict quality requirements for its production and use (Gies 1992). Representatives of the agricultural community have indicated their support for stringent guidelines such as these, which they feel will protect the quality of Ontario farmland (Gies 1992).

However, other groups have argued that the guidelines are too severe (i.e. unachievable), simplistic, may be contradictory and lack standard sampling and testing procedures (Kennedy 1991, Hanson 1991, Gies 1992). Curtis et *al.* (1991) recently reviewed the high quality compost standards for heavy metals and PCB in several U.S. states and it may be seen, by comparison, that the Ontario standards are usually 2 to 100 times more stringent. Hanson (19911 observed that the standards are based on the upper limits of natural metals in Ontario soils, although Kennedy (1991) pointed out that pig manure and muck soils in southern Ontario typically contain far more copper than the OMOE guideline limit. It must also be pointed out that the compost standards are based on concentrations per unit dry weight and not on some measure of the mobility or bioavailability of toxic substances (cf. Levi-Minzi et *a/.* 1992).

The use of MSW compost for tailings reclamation is an untested application which may not come under the new guidelines for aerobic compost. Further work is needed to define the most cost-effective organic waste products that will perform satisfactorily as an anaerobic reducing cover, without causing new environmental problems and health concerns. A major hurdle for the use of MSW compost may be gaining approval for' transportation and use of material from the major sources of compost in the south into northern Ontario. The OMOE guidelines in Ontario appear to leave some room for site-specific innovation:

> *The Guideline should be used along with good judgement and past practical experience in the handling of compostable wastes, their biodegradation and marketing the product. (p. iii)*
>
> *The Guideline is not intended to restrict process or equipment development. For highly modified composting techniques or new or updated technology differing significantly from current accepted'practices and processes, the proponent should demonstrate that the technology is consistent with the overall intent of the Guideline. (p. iii)*
>
> *Anaerobic cornposting is not included in the Guideline but all contaminant concentrations in the Guideline will apply to anaerobic systems. Operating conditions will be considered on a case-by-case basis. (p. 1)*

7.2 Federal Government Interests

The interests of the Canadian government with respect to mine lands are served primarily by the Ministry of Energy, Mines and Resources. Since the AMD problem was first addressed over two decades ago and with the formation of the MEND cooperative research program in 1988, a great deal of money has been spent on researching AMD and its solutions (Feasby *et al.* 1991).

The original MEND financial plan of $12.5 million was to be implemented over five years. Research is conducted by contracts to universities, consultants and through the contribution of funds and work-in-kind credits from government labs and mining companies. The mandate of MEND has been to find technical solutions to AMD through six technical committees: prediction, prevention and control, treatment, monitoring, technology transfer and international liaison. The implementation of AMD solutions and their socioeconomic implications are the responsibility of mining companies (and other institutions with AMD liabilities, such as governments), in accordance with provincial environmental laws and regulations. The federal government does not appear to have a direct interest in MSW management and the production and use of MSW compost.

Tailings and compost issues also extend into other areas of Federal government interest when health, fisheries, atmosphere and territorial lands are affected. These topics have not been reviewed here.

7.3 Municipal Government Interests

Ontario policy and legislation make MSW management a responsibility of the municipal level of government under the control of the OMOE. Municipalities must deal with planning, siting of facilities and costs of their local programs, although substantial subsidies may be paid by the provincial government to make them feasible.

A municipality has several interrelated demands to consider:

- provincial government regulations
- selection of appropriate technology
- cost to the municipal taxpayer
- public health and safety
- community image and property values
- public concerns and perceptions

It is clear that the acceptable approach for a municipality is an integrated waste management system which puts the highest priority on the 3-R's: reduce, reuse, recycle. The fraction that is recycled must receive close scrutiny to achieve the highest quality at the lowest cost. Markets for recycled materials must be carefully researched, developed and maintained to avoid the volatility of the marketplace. This is especially true of the organic waste fraction treated as compost, where public acceptance of safety and quality will make all the difference to its success. (Bourque & LeBlanc 1991).

The cost to the taxpayer, public health and safety and community image all become tied in with concerns that will be strongly expressed by a public not used to thinking about waste issues. A city may have one of the best integrated waste management plans in the country, but if it does not keep its citizens informed and give them a chance to be involved and be heard, it is going to have implementation problems (Mendenhall 1990, Goldstein 1990, Hunt 1990a,b). Golueke & Diaz (1989) stress the need for realism and genuine professionalism in dealing with waste management issues.

It is difficult to say what the municipal position might be in a northern community near a proposed compost cover solution for tailings, but it seems prudent to involve the district environmental officers and regional planners at the earliest stages of concept development.

7.4 Community Concerns

Members of a community may eventually be convinced by sound scientific and technical arguments which answer their concerns about environmental and public health issues (Fig. 8), but this is never the only form of community involvement with sensitive issues such as waste.

A New Brunswick study of public perception of compost showed that 70% thought that MSW compost was an acceptable product. However, this acceptance fell to 47% for composts derived- from industrial food wastes and further to 25% for compost derived from sewage sludge (Bourque & LeBlanc 1991). Clearly, sludge has a bigger image problem than MSW, despite considerable scientific evidence that, when properly made and handled, it is a safe and valuable agricultural product (Chaney 1990a, 1990b).

It may be that sludge has bad public relations for the same reason as skunks. Odour appears to be a key factor in community acceptance of a MSW facility (Curtis *et* al. 1991, Hunt 1990a). The public is equally concerned about health implications of the handling and processing of wastes. Unfortunately, North Americans, unlike many other cultures, usually treat waste as "out of sight, out of mind" and may have an exaggerated expectation of risk from this unfamiliar component of urban life. From an economic viewpoint, they may also be a bit overwhelmed by the size and complexity of the waste problems of the 1990's.

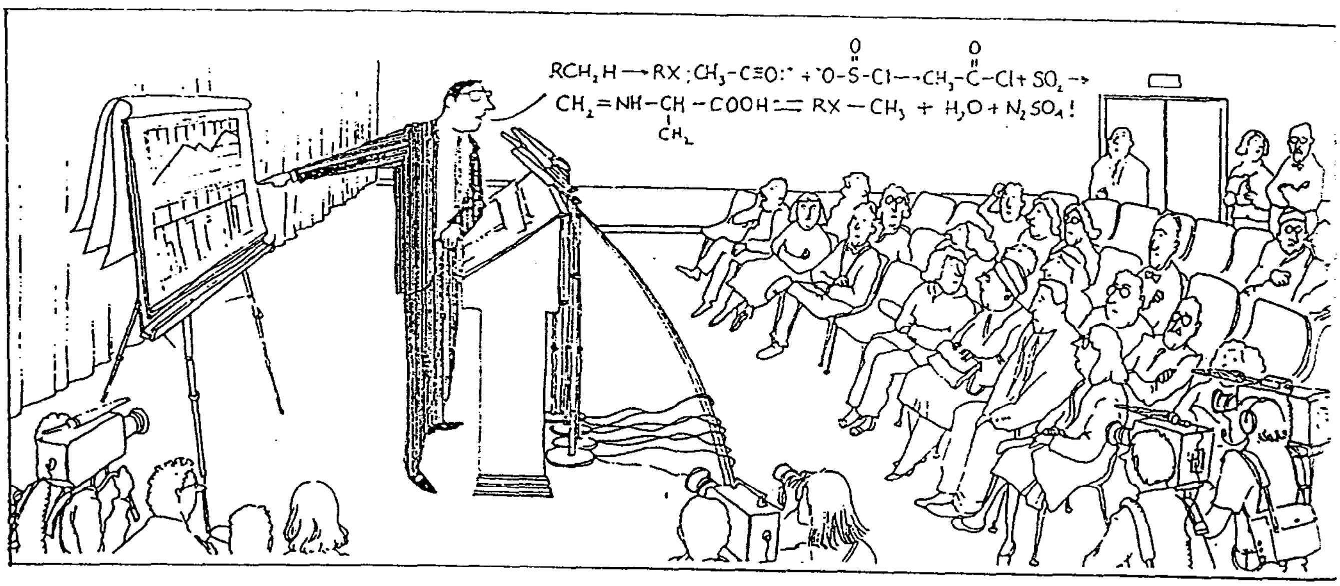

Figure 8. One level of community involvement (from Hunt 1990b).

Members of the public will always reserve the right to express their concerns based on their own priorities and sense of personal involvement. The first reaction may be a "NIMBY" response but it may be followed by well-researched, considered opinions. The most successful waste management projects have found mechanisms very early in the planning process for public input (Mendenhall 1990). Sufficient time must be allocated for: surveys, public meetings, draft guidelines to be distributed, briefs to be prepared, advisory groups to be set up and meet, outside expertise to be recruited, public information displays, evolution of ideas, informing and educating the media, political stances to be softened and persona! rapport to develop. Follow up after implementation (e.g. public recognition of contributors, public education, surveys and an effective complaint mechanism) may also be critical to a project's survival (Curtis et *al.* 1997, Hunt 1990b, Libbey 1991).

Two key mechanisms that appear to be successful are the public/environmental advisory committee and the pilot plant/trial process. Both of these approaches let interested citizens get involved, express their opinions and challenge the system to "show me before I'll believe you". This should be viewed as healthy because these citizens may offer valuable advice and insight in improving the process, or help in eventually selling the solution in the community. The aim should always be to develop "our solution", so that, when the final public hearing or approval is sought, there are no surprises.

Several communities, including the Greater Toronto Area and the city of Guelph have made detailed plans and conducted pilot studies for composting municipal solid waste (Municipality of Toronto 1991 [Appendix E], Cave and Associates 1991). Guelph has been running a pilot cornposting plant since 1990. Its objectives are to compare organic waste capture efficiencies and compost qualities for the two-stream and three stream collection methods. However, the amount of waste collected by the pilot study is small enough to permit efficient hand sorting of components which has led to a high quality of compost from both streams (Gibson 1991).

When allowed to participate, community members and groups will often contribute creative, positive ideas. In the draft Guelph Waste Management Master Plan (R. Cave and Associates 1991), public responses included the suggestion that "work be done on alternative technologies such as the use of MSW to reclaim stressed land". The Arthur Task Force suggested that "compressed MSW could be used as a subsurface layer for revegetation but that leachates would have to be contained and treated. Inert materials diverted from landfill would be suitable to reclaim mined out pits and quarries."

The draft Guelph plan also received interesting criticisms from the OMOE, that social criteria should include such items as risk perception, community cohesion and social responsibility. They also pointed out that the quality of the compost is based on the effectiveness of the public's separation efforts and also on the pre-processing of the wet wastes prior to composting. This echoes the observations of several other cities in North America which tried to implement some type of waste management system; quality is the result of a community effort (Mendenhall 1990, Goldstein 1990, Hunt 1990b).

The current OMOE Guidelines on compost were drafted with a view of cornposting as a *"complex process which requires considerable knowledge and skill for success."* The stated purpose of the Guidelines are, *"to provide human health protection while permitting compost production and use."* (OMOE 199 1; p. 1) The challenge for the compost tailings cover concept will be in proving the environmental and public health safety of placing and abandoning a large area of MSW compost and tailings. If immature compost or sewage sludge is used, the debate will be even more heated, as evidenced by the issues being raised and evaluated by several environmental groups in the U.S. (Spencer 1991a). The U.S. debate is often rooted in ideological positions on integrated solid waste management, but some groups seem to be willing to see if research and experience will show whether MSW composting can meet their criteria for safety and the 3-R's.

7.5 Compost Market Factors

After a strong initial start in the 1980's. recycling programs have experienced a saturation of markets and plummeting prices for material such as paper and glass. The collection infrastructure for recycled material is expanding faster than the industrial capability to use waste products (Ducey 1991). Some municipalities have turned to other ways to use materials which are now costing them money to collect rather than allowing them to make a profit. For example, in Virginia, newsprint and telephone books are a clean source of organic material that is sold to make a product called Hydromulch which is used as slurry to mulch, fertilize and reseed roadways, parks and industrial complexes (Trank 1991).

Municipal compost also runs the risk of being a product in search of a market. Compost is just now reaching the agricultural and horticultural markets where it must compete with generally cheaper and higher strength inorganic fertilizers, manure, peat moss, crop residues and topsoil as a soil amendment. In an analysis of the agricultural market for MSW and sludge composts, Collins (1991) concludes that, while the potential market is large, farmers have had a declining amount to spend per acre on soil amendments since the early 1970's. At the most, a farmer could afford $US6.50 a ton for low compost application rates down to below $US1 .OO per ton for heavy use, not including delivery! Since these costs are well below the market price for MSW compost and sewage sludge compost (i.e. $125 per tonne), only large subsidies to farmers will allow agricultural soils and crops to benefit from compost. When the economics are bad, questions about compost quality and safety are also paramount (Collins 1991).

Bourque & LeBlanc (1991) conclude that compost must be viewed in the context of solid waste management and not simply as a private business. undertaking. Municipalities don't really want to be in the compost selling business, but rather, just want to have an acceptable way to divert organic wastes from landfills and obtain revenue to offset the cornposting costs.

There is still a lot of fear and resistance in the community to the use of waste products such as compost and sewage sludge. Many quality cornposting businesses have gone bankrupt for lack of public acceptance (Bourque & LeBlanc 1991). Certainly, only the unrestricted use compost (Table 5a) will have the public's trust and marketability for household use in Ontario. Contaminated compost that does not meet provincial guidelines may end up only as expensive cover material for landfills, to everyone's dismay (Richard 1990). There will also be more pressure put on the waste management program to find ways to recycle more compostable materials into a higher grade of product and to minimize the potential for compost contamination with effective pretreatment (Richard 1990, Kennedy 1991).

Contaminated or "off-spec" compost is potentially usable by the mining industry for tailings and other land reclamation. For this large, long term market, municipalities might be willing to give the compost away or even pay to get rid of it (and provincial subsidies should not be ruled out since the Crown owns a great number of "orphaned" tailings sites). Another option is to produce immature or low grade compost, as cheaply as possible, specifically for tailings reclamation, and avoid the expense and trouble of high grade compost production. For example, the Guelph Waste Management Plan includes the strategy to develop opportunities for Wellington County and the City to dispose of their waste in northern Ontario sites. No current recipient sites outside the county have so far been identified (R. Cave and Associates 1991), provincial policy on exporting MSW notwithstanding.

7.6 Mining Industry Concerns

The mining industry in Ontario is being committed by legislation, and financial bond to responsibility for closure of mine properties in an environmentally safe manner (i.e. Ontario Mining Act 1991). Mining companies now have to assume responsibility and liability for the amelioration of damaged lands they own and return the property to a "productive" use. The goal of the mining companies is to have a closure plan, that when implemented, allows them to "walk away" from further liability for the environment. The alternative to abandonment is perpetual treatment which must be financed in advance and be shown to be technically feasible.

The toxic nature of tailings and waste rock which produce AMD is a problem which will last for hundreds of years if it is not treated or stopped. A compost layer on tailings may stop AMD but the mining company needs to be sure that it is not accepting another source of environmental liability with the use of compost and other wastes.

Mine lands, such as tailings, are already disturbed and very environmentally-stressed. The use of high quality MSW compost may be the safest approach but it also may be prohibitively expensive or the material may not be available in sufficient quantity for a viable implementation. One alternative is to use cheaper immature or contaminated compost, which would ordinarily not be approved for urban or agricultural use, if it can be demonstrated that it does not significantly aggravate the existing tailings problems. The MSW compost cover concept should not be rejected on principle but put to a reasonable test through scientific experimentation.

With respect to the OMOE Guideline for aerobic compost, this may require the creation of a new category of low grade compost specifically for use in tailings reclamation. A dialogue between the mining industry and environmental agencies should begin now as experimental investigations are done. Molot (1992) recommended that composting and tailings reclamation policies should be coordinated by a policy planning group consisting of representatives from the mining industry, cornposting industry (municipalities), OMOE, Ontario Ministry of Northern Development and Mines, and Environment Canada.

7.7 Summary

The regulatory, economic and social aspects of the use of MSW compost may be just as important as the technical aspects in the use of compost as a cover layer on tailings. Ontario government policy on solid waste management requires municipalities to work aggressively to divert 50% of garbage from landfills by the year 2000. Municipal solid waste composting is seen as an important component of waste diversion, although it may be less than 20% of the waste stream. The OMOE has issued guidelines for the production of MSW compost, setting some of the strictest quality standards in North America for heavy metal and PCB content. There is an impiied flexibility in the guidelines document, however, that may make allowances for anaerobic composting and innovative technologies and uses.

The federal and provincial governments, through the Mine Effluent Neutral Drainage research program, is encouraging mining companies to undertake creative solutions to the problems of tailings reclamation, especially as it relates to acid mine drainage. The Ontario Mining Act 1991, now requires closure plans for mine properties which include either abandonment measures or perpetual treatment of environmental problems. All closure plans must be backed up by financial guarantees that will pay for its implementation, forever.

The interests of both the municipalities, seeking to recycle solid waste as compost, and the mining companies, seeking techniques for abandonment of tailings sites, may overlap in a “win-win” solution by the use of MSW compost as a cover layer on tailings. However, the views of the community must also be taken into account. The municipal government must be sensitive to many factors including cornposting costs, public health and safety, community image and public perceptions. Community involvement is a key factor in public acceptance of issues which may affect them or the environment. Wastes such as compost and sewage sludge have a bad public image and people perceive unacceptable risks and nuisance from these products. Two mechanisms of community involvement that seem to work well are the public advisory committee and the pilot plant/trial process to allow concerned citizens to ask questions, become involved and see results for themselves.

Even if technical solutions are found and community concerns are met, factors of the marketplace, such as cost and availability, may dictate whether MSW compost is a cost effective solution for AMD problems and tailings abandonment. The production of high quality MSW compost may be a money-losing product for municipalities. Mining company use of compost would be more attractive if immature or lower grade compost could be used in the tailings cover. This compost could be taken out of the MSW stream at an earlier, cheaper point and used specifically for tailings reclamation. However, the government policy and regulations concerning MSW compost may have to change to reflect this unique use.

8. CONCLUSIONS

1. The problem of acid mine drainage (AMD) from sulphide tailings has not been solved by the techniques of revegetation and liming. It is now recognized that AMD must be either permanently stopped or treated perpetually by new methods, such as preventing oxidation of sulphides, preventing groundwater flow through tailings or the use of wetland systems to neutralize AMD.

2. Techniques are being sought to create an oxygen barrier on tailings to prevent atmospheric oxygen, or oxygen dissolved in water, from penetrating to the zone of oxidation. However, many tailings sites are not amenable to effective methods of preventing pyrite oxidation, such as flooding and the formation of artificial wetlands. Some of the new forms of oxygen barriers under development will maintain a layer of saturated material on top of the tailings and essentially stop oxygen diffusion. This layer must consist of fine, silt-like material which is often expensive or not locally obtainable in the tailings areas of the north.

3. Municipal solid waste (MSW) compost is proposed as a material which could be used as a cover for tailings that may permanently prevent sulphide oxidation and the resultant AMD. The compost layer could function in five ways:

(1) *Physical* oxygen *barrier* - the compost would be saturated with water over at least part of its depth so that the limiting factor in oxygen diffusion would be the diffusivity of oxygen in water;
(2) Oxygen-consuming *barrier* - the continued decomposition of compost creates a large biological oxygen demand that acts as a sink for diffusion of atmospheric oxygen or oxygenated water;
(3) Chemicalinhibition - compounds and decomposition products in the MSW compost that leach into the tailings inhibit the growth and metabolism of sulphate-producing bacteria;
(4) Chemical amelioration - organic constituents in the MSW compost that can cause the dissolution of ferric iron and prevent indirect ferric sulphide oxidation and acid generation;
(5) Reduced water infiltration - reduced hydraulic conductivity of compacted compost may prevent infiltration of precipitation thus decreasing tailings groundwater flow.

A key feature of two of the proposed compost cover layer designs is the compaction of compost by an overburden of sand/gravel. The maintenance of anoxic conditions may allow anaerobic processes to reduce many oxidized compounds in the upper oxidired tailings layer although metals may be mobilized.

4. MSW compost and municipal (non-industrial) sewage sludge and compost may contain significant quantities of heavy metals, toxic chemicals and pathogens. The risks of these contaminants are largely a function of the quality of the feedstocks, the optimization of the composting process and environmental availability. For MSW compost, separation of organic waste from non-biodegradable garbage and hazardous chemicals is essential in producing uncontaminated, high-quality compost. Sewage sludge may also become a high-quality compost product if pathogens are killed and if the wastewater stream is uncontaminated by industrial effluents. The quality of leachates from MSW compost and other organic waste components used on tailings will require careful experimental examination to ensure public and environmental safety. Early and genuine involvement by the community is essential to the acceptance of any tailings reclamation plan involving MSW compost or other organic wastes.

5. Other waste materials offer some or all the same benefits as MSW compost (or as an additional co-composting component) as an oxygen barrier. Forest industry and paper mill wastes are plentiful and a nuisance in many of the areas of Canada where tailings are located. Peat is a common and abundant natural material in bogs throughout the north and may be useful for tailings covers if it can be managed as a renewable resource. Tailings leachates will have to be tested for harmful compounds from these wastes as well as the beneficial effects on AMD.

6. MSW compost or other organic wastes will be used by the mining industry only if they provide a permanent and cost-effective solution to tailings abandonment. Even if the municipalities provide MSW compost at no charge, transportation costs from the major sources in the south to tailings sites in the north may be prohibitive. The use on tailings of much cheaper, immature MSW compost is suggested as a way of reducing the cost of composting to the municipality and of guaranteeing a large supply of compost for tailings reclamation. Experimental work with different grades of MSW compost will be necessary to verify the efficacy and safety of this approach. Ontario government policy and regulations, that currently prevent the export of waste from a municipality, should be examined with respect to tailings reclamation.

9. RECOMMENDATIONS

1. Laboratory work using instrumented leaching columns is necessary to test the physical aspects and optimitation of the compost cover layer models:

   a) Effects of various depths of overburden and compost on compost compaction, hydraulic conductivity and compost moisture characteristic,

   b) Effectiveness of each compost layer model in maintaining anoxic conditions in the tailings under static conditions,

   c) Determination of the water balance and pattern of saturation of the cover system for a simulated climate year,

   d) Effects of addition,of other organic wastes, (e.g. sawdust, composted sewage sludge, composted paper mill sludge) on the maintenance of anoxic conditions,

   e) Measurement of the physical characteristics of each cover layer trial.

2. Laboratory analyses of leachate composition from unsaturated and saturated compost layers, containing compost of various degrees of maturity:

   a) Determination of the degree of compost maturity,

   b) Regulation 309 leaching test (Environmental Protection Act),

   c) Heavy metal spiking of compost to determine the degree of heavy metal retention,

   d) Simulated acid rain effects on leaching of toxic compounds,

   e) Bioassays of the toxicity of tailings and compost leachate.

3. Laboratory studies of chemical processes within tailings using the optimal cover layer design:

   a) Characterization of the crystallinity of oxidized tailings and the distribution of adsorbed trace elements within the tailings,

   b) Effects of redox potential and acidity changes on solid phase chemical speciation and the composition of tailings pore water and leachate,

   c) Measurement or simulation of the bacterial activity in the system.

4. Field lysimeter studies of the optimal compost cover layer design, as determined by laboratory experiments, should be conducted in the Nickel Rim tailings:

a) Effects of overburden layer on compost layer compaction, water balance and degree of moisture saturation,

b) Effects of ambient temperature and precipitation regime on anaerobic processes and acidity,

c) Quantity and quality of compost layer leachate and tailings leachate.

5. Discussions should be initiated by Falconbridge Ltd. with provincial government ministries, municipal government and the community concerning the use of MSW compost in tailings reclamation.

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APPENDIX A

Glossary and Abbreviations

AMD	acid(ic) mine drainage - acidic leachate water primarily from sulphide tailings or waste rock
aerobic	a process or organism which requires molecular oxygen
AEV	air entry value - water tension (potential) at which the largest pores of a saturated porous medium begin to drain and air enters to fill the pores
anaerobic	a process or organism which can function in, or depends on, the absence of molecular oxygen
anoxic	lacking molecular oxygen
BOD	biological oxygen demand - the oxygen consumption rate of a material due to microbial respiration
COD	chemical oxygen demand - the oxygen consumption by chemical processes not involving organisms
C/N	the ratio of carbon atoms to nitrogen atoms in a substance
cornposting	accelerated degradation of heterogenous organic matter by a mixed microbial population. in a moist, warm, aerobic environment under controlled conditions to form a soil-like product rich in in humus and microbial life
co-composting	cornposting of two or more waste stream simultaneously
curing	the process by which materials more resistant to microbial break down are created (also known as maturation)
E_h	redox potential of a solution - a measure of the tendency of a solution to donate electrons to a reducible substance or to accept electrons from an oxidizable substance
ferric	compounds or ions of the Fe^{3+} form of iron
ferrous	compounds or ions of the Fe^{2+} form of iron
humus	the complex organic constituent formed by the decomposition of organic material whose anatomical features cannot be recognized
hydraulic conductivity	a measure of the ease with which a material conducts water
leachate	liquid formed by water percolating through a porous substance and extracting dissolved or suspended materials from the solid phase
MEND	Mine Effluent Neutral Drainage - federal & provincial AMD abatement research program

moisture characteristic	the relationship between water content and pressure (tension, head, potential) in a porous material
MSW	municipal solid waste (formerly garbage or refuse)
OMOE	Ontario Ministry of the Environment
oxidation	a chemical process whereby a compound transfers electron(s) to an oxidizing agent (which becomes reduced)
pathogen	a microorganism, virus or parasite capable of causing disease or nuisance in humans (in other organisms it is often called a pest)
PCB	poly-chlorinated biphenyl - a synthetic toxic organic molecule
porosity	total pore volume divided per unit total volume of the porous material
redox	coupled reduction and oxidation reactions
reduction	a chemical process whereby a compound receives electron(s) from a reducing agent (which becomes oxidized)
saturation	(degree of) - the proportion of pore volume filled with water'
sludge	a semi-liquid residue remaining from the treatment of municipal and industrial waste water
stability	the state of decomposition of organic matter, primarily dependent on the microbial population present and the available substrates
sulphide	an unoxidized compound which includes sulphur
3R's	a waste management strategy which emphasizes reduction, reuse and recycling
three-stream	a waste collection system in which there is separate collection of recyclables, organic materials (wet) and non-recyclables (dry)
two-stream	a waste collection system in which there is separate collection of recyclables and non-recyclables (e.g. "blue box" program)
waterlogged	the condition of complete or almost complete saturation
water table	the depth under the surface where ground water saturates the soil
windrow	an elongated pile of organic waste being composted, usually outdoors

APPENDIX B

Prevention and Control of Acid Mine Drainage From Tailings with Municipal Compost: Policies, Programs and Viability

PREVENTION AND CONTROL OF ACID MINE DRAINAGE FROM TAILINGS WITH MUNICIPAL COMPOST: POLICIES, PROGRAMS AND VIABILITY

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EXECUTIVE SUMMARY

The Faculty of Environmental Studies at York University has been engaged by Rio Algom Limited and Laidlaw Waste Services to investigate the feasibility of using composted municipal organic waste (food and yard waste) to aid in the reclamation of mine tailings. Tailing reclamation represents a potentially unlimited market for municipal compost and may assist municipalities in meeting provincial waste diversion targets. This study reviews the composition and distribution of organic waste in Ontario, organic waste collection methods, government waste management and tailings reclamation policies, compost quality, markets for municipal compost, feasibility of using sewage sludge, transportation, cost analysis and tailings reclamation programs and methods.

When sulfide-bearing mine tailings are exposured to air and water, adjacent surface waters may become contaminated with high levels of acidity and metals. Since biological communities are greatly affected by highly acidic, metal contaminated water there is a compelling need to seek and apply corrective measures. The seriousness and extent of the acid mine drainage (AMD) problem has prompted the mining industry along with the federal and several provincial governments to cooperate in investigations of innovative methods for long-term, environmentally effective management of tailings which reduce or prevent the formation of AMD and minimize long-term active management of tailings sites after mine closure.

Two tailings reclamation methods appear promising. Flooding of mine tailings to create artificial wetlands has been proposed by Rio Algom Limited because it offers an effective means of preventing and attenuating AMD by reducing the exposure of tailings to oxygen. A second method utilizes a layer of fine-gnined material above coarser material. The fine cover material is designed such that it is maintained in a moisture-saturated state regardless of the depth to the water table (i.e. drainage is limited) and therefore minimize exposure of underlying tailings to oxygen. In either case, erosion of tailings material is reduced,

The effectiveness of flooding and engineered covers in limiting oxygen supply and reducing erosion would be greatly enhanced by application of organic material which would increase productivity and biological diversity; however, there is a shortage of organic material near many mines situated on the Precambrian Shield in northern Canada.

A partial solution to the shortage of organic material may lie with composting municipal organic waste which comprises about 24% of the total non-hazardous municipal solid waste stream. Composting is a process which produces a relatively stable organic end product similar to the organic component of soils and which has some beneficial uses to society. At the present time, composting diverts a very minor amount of waste from landfill in most Canadian municipalities.

Urban communities are finding it increasingly difficult to dispose of growing amounts of municipal solid waste using the traditional method of landfilling. They are under increasing government and public pressure to divert waste from landfill by reduction, recycling and reuse. In Ontario, the provincial government has decreed that municipalities must divert 50% of their waste from landfill by the year 2000. Given that much of the waste stream is compostable, many municipalities may find large scale composting attractive if long-term markets can be secured.

The benefits of cornposting to both the mining industry and municipalities are illustrated by the following example: an efficient organic waste collection system in a community of 100,000 people could theoretically produce a maximum of approximately 17,000 tonnes of organic waste or 8,500 tonnes of compost per year which would cover 1.7 hectares to a depth of 1 meter. Metro Toronto could produce up to 212.000 tonnes of compost annually which would cover 42 hectares to a depth of 1 meter. Given that approximately 15,000 hectares of sulfide-bearing tailings are in need of reclamation in Canada, unlimited composting application could occur for many decades.

The situation is timely for both the mining industry and municipalities currently engaged in developing environmentally sound management practices to consider large scale application of municipal compost to tailings impoundments. Composting would go a long way to meeting the provincial government's target of diversion of 50% of municipal waste from landfill and incineration.

Conclusions

1. Construction of artificial wetlands and engineered covers are, in principle, viable techniques for AMD prevention and attenuation. The wetland technique has been successfully applied in the U.S. to treat acidic effluent rather than prevent AMD formation. Retention of metals other than iron is very site specific and is apparently a function of biological structure.

2. The effectiveness of artificial wetlands is enhanced when organic material is added. Organic material would also help to stabilize soils by promoting growth of vegetation. However, sufficient quantities are in short supply near many tailing sites. Composted municipal organic waste may be a suitable source of organic material for tailings reclamation projects.

3. Solid waste management policies are rapidly developing in Ontario to the point where large scale composting is being seriously considered by provincial and municipal governments in order to meet provincial waste diversion targets. If municipalities throughout Ontario are to be persuaded to engage in large scale composting activity to meet provincial targets they must be assured that non-landfill uses are available. Tailings reclamation is proposed as a suitable alternative/addition to agricultural and horticultural markets. Furthermore. tailings reclamation may be an acceptable non-landfiil use for metal-contaminated compost.

4. The 'operationally obtainable' organic waste fraction is assumed to be 17% of the total waste stream in Ontario. This percentage is derived by assuming an organic waste fraction of 24%, a participation rate of 90% and a capture efficiency of 80% across all sectors in Ontario. The 'operationally obtainable' organic waste fraction could produce approximately 680,000 tonnes per year of compost assuming a 50% weight loss during composting. All of Ontario's annual compost production would cover 136 hectares to a depth of 1 m assuming a bulk density of 0.5 tonnes/m'. Given that approximately 15,000 hectares of tailings are in need of reclamation. unlimited cornposting application could occur for many decades. About 30.000 tonnes of composted sewage sludge could also be produced annually.

5. The three stream waste collection method will most likely be implemented in Ontario. The method should minimize contamination levels and produce compost which meets the Ministry of the Environment's guidelines for unrestricted use. Nevertheless, some compost batches will likely not meet the guidelines for unrestricted use.

6. The legal and environmental ramifications of metal-contaminated compost application to tailings must be addressed.

7. The rate of compost application to flooded tailings should be such that reducing conditions capable of supporting sulfate reduction are well within the organic layer. This operational criterion is best translated into tonnes/m* empirically.

Recommendations

1. Coordination of composting and tailings reclamation policies is essential for success. A policy planning group should be formed consisting of representatives from the mining industry, cornposting industry, municipalities (perhaps from an umbrella organization of municipalities), the Ontario Ministry of the Environment (Water Resources Branch, Waste Management Branch, Waste Reduction Office and possibly Northeast and Northwest Region offices), the Ontario Ministry of Northern Development and Mines, Environment Canada and Energy, Mines, Resources Canada (UNMET).

2. Criteria should be developed governing conditions under which contaminated compost is deemed acceptable as tailings cover. Liability concerns should also be addressed.

3. Test plots and pilot artificial wetland projects are urgently needed to evaluate the effectiveness of compost application using permanently flooded amended (treatment) and unamended (reference) ponds. The pilot projects should monitor long-term changes in water quality (pH, Gran alkalinity, metals, nutrients, oxygen, temperature, conductivity, dissolved organic carbon, sulfate, major cations, etc.), sediment chemistry, sediment oxygen consumption rates, biological productivity and community structure, metal bioaccumulation in selected species,

toxicity of standing waters (e.g. rainbow trout bioassays), and acid neutralization and metal attenuation rates and processes. Field studies should consider pond design features which promote biological diversity. The collaboration of aquatic ecologists, microbiologists, hydrogeochemists and biogeochemists will be necessary. University participation should be sought.

Questions to be addressed:

a. minimum/optimum compost application rates.

b. metal bioaccumulation in food chain, e.g. fish. waterfowl, macrophytes, and toxicity of standing waters.

c. pond design features for optimal AMD attenuation/prevention: e.g. optimum water residence times, shoreline complexity and varying depth to promote biological diversity.

d. relationship of biological diversity to AMD attenuation/prevention.

e. relative importance of various neutralization/metal attenuation processes.

f. seasonal effectiveness of wetlands.

4. Test plots and pilot projects are urgently needed to evaluate the effectiveness of compost application to engineered covers.

5. Organic wastes should be solicited for pilot projects and test plots. Composted food processing wastes and sewage sludge should be considered as potential sources due to the present lack of sizable source-separated municipal collection programs. Compost derived from mixed municipal waste is not recommended.

APPENDIX C

Guideline for the Production and Use of Aerobic Compost in Ontario

DRAFT

GUIDELINE FOR THE PRODUCTION AND USE OF AEROBIC COMPOST IN ONTARIO

ONTARIO MINISTRY OF THE ENVIRONMENT

WASTE REDUCTION OFFICE

APRIL, 1991

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Introduction

Natural biological decay of waste or dead plant and animal life has been a feature of the environment since the first emergence of life.

Various micro-organisms can decompose complex organic matter, including themselves, into much simpler, more stable chemical forms.

In the early years of this century, engineers learned to use these natural reactions to provide inexpensive, safe and efficient methods of treating waste.

These developments led to widespread use of the activated sludge process for treatment of municipal and industrial liquid waste streams. In addition, aerobic and anaerobic digestion processes, are common features in water pollution control plants, for stabilizing sludge. The biological processes, and the equipment and design parameters required for their control and optimization, are well understood as evidenced by the wealth of scientific and engineering literature available.

Anaerobic and aerobic cornposting of sludges and solid wastes are variations of the above processes, where the same goal of reducing complex organic matter into simple, stable compounds is sought by using micro-organisms. Cornposting requires its own.design parameters, operating methods and equipment to. provide the optimum environment for biological degradation of waste.

Cornposting is also a well researched, well understood process among scientists and engineers. It is not, however, as well understood at the operational level. This is mainly because, until relatively recent times, landfilling wastes was more expedient than other means of waste management, including cornposting. With the advent of "garbage crises" in North America however, allied with increased awareness and concern regarding the long-term effects of landfilling, there has been renewed interest in landfilling alternatives.

Ontario has implemented the 3R's principles (Reduction, Re-use, Recycling) to improve waste management and meet current and future needs. The 3R's apply to both municipal and industrial wastes and are already succeeding in diverting wastes from disposal. The Ministry of the Environment's goal is to divert at least 50% of wastes from disposal by the year 2000.

There will be a continuing need to provide alternative waste management methods for materials not readily amenable to 3R's initiatives. Some disposal will still be required, but composting will likely be attractive for treating biodegradable solid organic wastes. Thus, composting is currently experiencing "re-discovery" and will likely see wider use in the near future..

While this is a welcome development, caution must be exercised. Seemingly simple on the surface, cornposting is a complex process which requires considerable knowledge and skill for success. In the past, many operations have failed due to inappropriate application of the process, poor design, improper equipment selection, poor location of plants, or for other reasons. The few bad operations caused potentially good operations to be dismissed as having the same problems.

For example, there was considerable interest in composting during the 50's and 60's but this had faded by the late 60's. This was due to bad experiences with poorly engineered and operated facilities for which overly optimistic expectations and claims were made. In addition, the failure to develop markets compounded problems and caused financial problems.

Thus, cornposting requires a rational engineering approach and each system must be based on and developed using well defined engineering design, operation, monitoring and analytical principles.

It is vital, therefore, that both public and private sector waste management organizations and interests recognize this, and approach cornposting as a waste management alternative in a rational, realistic manner.

SUMMARY

The Guideline has been prepared to assist cornposting proponents, MOE staff and staff of other agencies in the selection and/or approval of appropriate aerobic cornposting methods and the production of quality compost based on good operating practices, compost characteristics, and current MOE legislation.

The Guideline was derived from previous MOE guidelines, experience gained by the MOE from its own cornposting operations, discussions with compost operators in Ontario and elsewhere, review of other agencies' requirements, and an in-depth review of the literature.

It provides a review of regulatory requirements for aerobic cornposting and a brief overview of the process, highlighting parameters critical to the success of composting.

The information will aid in the attainment of high quality compost product. Value added markets for the product may require development, but offer the best long-term potential for rendering the process economically viable.

The MOE suggests that proponents discuss project proposals with MOE staff as an initial step to obtain regulatory and technical advice. Also, public meetings and consultation with neighbours of the proposed site will assist in avoiding potential problems and delays.

It is noted that in time, the compost quality requirements may be updated as better information becomes available.

The Guideline should be used along with good judgement and past practical experience in the handling of compostable wastes, their biodegradation, and marketing of product.

The Guideline is not intended to restrict process or equipment development. For highly modified cornposting techniques or new or updated technology differing significantly from currently accepted practices and processes, the proponent should demonstrate that the technology is consistent with the overall intent of this Guideline.

1.0 PURPOSE

The purpose of the Guideline is to provide environmental and human health protection while permitting compost production and use. ,

2.0 OBJECTIVE

The objective of the Guideline is to ensure that cornposting projects and compost use are managed with due regard to process conditions and chemical and physical characteristics, to prevent contamination of the environment; The Guideline ensures that cornposting is allowed to develop as a significant waste management option to contribute to Ontario's waste diversion goals.

In addition, the Guideline provides a reference document to ensure that the approval of. systems for the production, handling and use of compost, is managed in a consistent manner throughout Ontario.

3.0 SCOPE

For the purposes of the Guideline, cornposting is defined as an aerobic biological process, conducted under controlled, engineered conditions designed to decompose and stabilize the organic fraction of solid waste.

Compost is defined as the material produced by an aerobic cornposting process, which can be used as soil amendment, artificial top soil, or for other similar uses.

Anaerobic **composting**, is not included in the guideline but all contaminant concentrations in the Guideline will apply to anaerobic systems. Operating conditions will be considered on a case-by-case basis.

This Guideline does not apply to backyard cornposting by householders.

The Guideline discusses generic cornposting technologies, major operating parameters, and sampling and chemical analyses. Reporting of results, monitoring of processes, and assessment of potential off-site impacts are also included.

Relevant legislation and standards are referenced in discussion of the approvals process.

Agricultural wastes are exempted from Regulation 309 of the Environmental Protection Act, and the Guideline does not apply to them.

Process operating parameters and chemical and physical quality for compost use are provided.

4.0 APPROVALS AND PERMITS

4.1 Approvals

The following are the main Provincial statutes which apply to composting operations:

The Environmental Protection Act, (EPA)
The Environmental Assessment Act, (EAA)
The Ontario Water Resources Act (OWRA)
The Consolidated Hearinss Act, 1981

Proponents should also be aware of the Ontario Municipal Board Act, the Plannins Act, the Expropriations Act, and the Federal Fertilizers Act.

4.2 Environmental Assessment Act (EAA)

The Environmental Assessment Act applies to provincial and municipal projects and may also apply to private sector projects at the Minister of the Environment's discretion. The threshold level for the application of the EAA to composting facilities is a capability for 200 or more tonnes per day of residual waste generation from the facility. If the Minister deems the site to be environmentally significant, the site may require an environmental assessment, irrespective of the 200 tonnes per day threshold.

For further information on the EAA process, staff of the MOE Environmental Approvals and Environmental Assessment Branches should be consulted.

4.3 Environmental Protection Act (EPA)

Part V of the Environmental Protection Act and Ontario Regulation 309 govern the disposal and processing of wastes at Waste Disposal sites for. which Certificates of Approval are required. A composting site is a Waste Disposal Site (Processing); (Form 1645/80). A cornposting site is not a final disposal site. Hearings are therefore not mandatory under the EPA, but discretionary hearings are held when the Regional Director considers them necessary. MOE policy 14-01-01 indicates how this discretion is exercised.

Certain requirements of the Guideline are waived for **leaf and yard waste** cornposting facilities as shown below. However, the local MOE District Office must be informed of and consulted on these facilities.

The projects are subject to Sections 6 and 8 of the Guidelines although monitoring requirements may be relaxed to one time for each batch. The compost quality specifications in Section 7 are waived, except for subsection 7.3 and 7.4, the metals and organic chemicals criteria respectively;"

In addition, these facilities must comply with siting criteria and operating information as described in Section 5 of the Guideline. Occupational health and safety requirements must be observed.

It is strongly recommended that the overall intent of the Guideline be followed. Minimum operating, monitoring and analytical standards are necessary and should be selected and implemented to ensure the avoidance of nuisance conditions, and production of useful compost.

The waiving of certain requirements of the Guideline for leaf and yard waste cornposting must not be construed as meaning these facilities do not require appropriate engineering, operation and monitoring. The waivers are based on the perception that the same degree of engineering, operation, analytical, monitoring, and approvals requirements are not necessary when compared with mixed municipal solid waste. facilities.

Waste Management Systems Certificates of Approval are required for handling all waste materials, including those used for compost production, from their sources (generators) to the cornposting facility.

Compost will be considered-a waste under Regulation 309's *'processed organic waste" definition, if it fails to meet the Guideline. In this case, the MOE will require Waste Disposal Site approvals for locations where compost is applied, and Waste Management Systems approvals for handling it. In most cases, however, if the cornposting site obtains all MOE approvals and meets the Guideline, the compost will be deemed to be a product and not a processed organic waste. In this case, application site and system approvals are exempted.

The cornposting proponent will also require a Certificate of Approval (Air) under Section 8 of the Environmental Protection Act (Form 1147 4/76). This general air management regulation sets standards for acceptable levels of airborne emissions (stack or fugitive), noise, and odour. Applicants should consult with MOE regional staff.

Cornposting processing areas should be separated from other land use zones by buffer zones, which should be included as part of the project. Alternatively, the compost processing area may be enclosed and collection and treatment of gases and other emissions may then be necessary.

4.4 Ontario Water Resources Act (OWRA)

Approval under Section 24 of the Ontario Water Resources Act for the collection, treatment and disposal of run-off or discharged waters will be required. MOE regional staff should be consulted.

4.5 The Consolidated Hearinas Act, 1981

If a project is subject to two or more hearings, before more than one tribunal, under statutes listed in the Consolidated Hearinas Act, 1981, and has been planned such that the issues can be considered in a common forum, the proponent may wish to use the mechanisms of the Consolidated Hearings Act, to avoid more than one hearing.

4.6 Applications for Cornposting Sites

Applications should be sent to the local MOE District Office for review. In addition, comments should be solicited from the local Medical Officer of Health and the Ministry of Labour, to ensure that the health and safety of the operators and the public are adequately protected.

4.7 Permit by Rule

This is a streamlining process expected to be in place in early 1992. Certain types of cornposting projects, will be exempted from the full EPA Part V Approvals process provided they comply with the conditions indicated by a Permit by Rule procedure.

5.0 SITING CRITERIA

The following criteria are included in the Guideline only as examples. Proponents should consult local MOE District Office staff to ensure and confirm up to date criteria. Such criteria may be required during the approvals process. In addition, plant operating information will be required. Examples of this are shown in Appendix 2.

5.1 Location

5.1.1 Maps

1. A regional map (minimum 1:62,500) showing:

   i) the entire service area of the proposed facility both existing and proposed);

   ii) existing and proposed collection, processing and disposal operations;

   iii) the closest population centres;

   iv) transportation systems including highways, airports and railways.

2. A vicinity map (minimum 1:24,000) showing. the area-within one mile of the facility:

   i) boundaries
   ii) -zoning and land use
   iii) residences, commercial/institutional/ industrial operations
   iv) surface waters
   v) access roads, bridges, railroads, airports, historic sites
   vi) other existing and proposed man-made or natural features

3. A site plan (minimum 1:2,400) with five feet contour intervals showing:

   i) property lines
   ii) existing and proposed soil borings, monitoring -wells, drainage, culverts
   iii) buildings 'and appurtenances, parking areas
   iv) fences, gates, roads
   v) storage -and loading facilities or areas
   vi) existing and proposed elevation contours and topography indicating run-off
   vii) direction of prevailing winds
   viii) residences
   ix) potable wells, surface water bodies

5.1.2 Buffer Zones

Cornposting facilities, especially open air operations, should provide minimum distances from the nearest individual residential dwelling and from any area of residential development. Indoor operations may require a smaller buffer zone.

Facilities should also be adequately spaced from any water well, or water course. Required distances should be determined by consultation with MOE District Office staff.

6.0 COMPOSTING OPERATING REQUIREMENTS

6.1 PATHOGEN REDUCTION

Windrow and Static Pile Composting

The material must be maintained at a temperature between 55°C and 60°C throughout the pile, for at least fifteen (15) consecutive days during the cornposting process to inactivate pathogens. Windrows must be turned over at least five (5) times during this period. Static piles which are not turned must meet the same temperature requirement, again throughout the pile.

In-vessel (Mechanically Mixed and Aerated) Composting

A minimum 3 day retention time at a temperature between 55° C and 60° C is required. The lower time requirement recognizes the better reliability of in-vessel systems with respect to mixing and process control.

If temperature monitoring shows the above has not been achieved, the compost must be disposed or re-processed.

6.2 Temperature

In the high rate stage of cornposting, temperature must be maintained between 55°C and 60°C to provide for both bacterial growth and pathogen inactivation. For batch windrow and static pile systems, temperatures must be recorded daily for the first 15 days, then weekly until the processing ends. For continuous systems, daily temperature monitoring is recommended. Batch in-vessel systems require daily temperature monitoring for the entire retention period.

6.3 Oxygen Requirements

Oxygen levels must be maintained above 10% (v/v) and normally will be controlled in the 12% to 18% range. It is noted that different wastes may have different oxygen requirements and that aeration intensity may be altered to suit.

6.4 General

In the case of windrow or static pile processes the operator shall ensure:

- that the rows or piles are physically sized to be manageable by the proposed equipment
- that space between the rows or piles allows vehicles access, including fire fighting equipment.

6.5 Uncontrolled Decay

Simple exposure of solid organic waste under non-engineered conditions resulting in uncontrolled decay is not considered to be composting and will not be permitted.

7.0 COMPOST QUALITY SPECIFICATIONS

7.1 Introduction

The following specifications must be met by the final product in the form it leaves the composting site, if the compost is to be used on an unrestricted basis.

Lower quality compost will be deemed to be processed organic waste and will only be applied to a properly approved organic soil conditioning site e.g. to lands zoned commercial or industrial (including institutional or governmental operations, land reclamation projects as well as agricultural).

7.2 ORGANIC MATTER DESTRUCTION

No single number can describe satisfactory organic matter destruction, as destruction is proportional to the organic content of the raw feed. The per cent reduction in organic content will be measured by loss on ignition solids analyses and calculated by the expression:

$$100 \left[1 - \frac{(\%\ \text{ash in Raw} \times \%\ \text{VS in Treated})}{(\%\text{VS in Raw} \times \%\ \text{ash in Treated})} \right]$$

where: VS = Volatile Solids
Raw = Raw feed
Treated = Compost product

7.3 Metals

The metal content of the finished compost will not exceed the following concentrations as calculated on a dry weight basis:

Metal	Concentration (mg/kg dry wt)
Arsenic	10
Cadmium	3
Chromium	50
Cobalt	25
Copper	60
Lead	150
Mercury	0.15
Molybdenum	2
Nickel	60
Selenium	2
Zinc	500

The metal content of each raw material fed to the cornposting process also shall not exceed the above concentrations. No individual waste component, additive, inoculant, etc., may exceed the above.

7.4 Organic Chemicals

The organic chemical content of the compost shall not exceed the following concentrations as calculated on a dry weight basis:

Parameter	Concentrations (mg/kg drv wt)
PCB	0.5

(Further organic chemical parameters to be included as they become available)

7.5 Non-Biodesradable Particulate Matter

The finished compost must contain no material of a size or shape that can cause human or animal injury, or damage to equipment.

The non-biodegradable particulate content of the compost shall not exceed the following:

Concentration

Parameter	(% dry wt)
Plastic	1.0
Other	2.0

7.6 Compost Particle Size < 25 mm

7.7 Stabilitv

Various means of determining stability are suggested in Appendix 3. Any of the methods alone or in combination may be used to demonstrate stability. If no determination of stability is made, the compost must be cured for a six month period.

7.8 Other Parameters (These are not specifications, but are ranges of characteristics typical of good compost quality)

7.8.1 Mineral Content

Parameter	Typical Minimum Concentrations (% drv wt)
Total Nitrogen	0.6
Total Phosphorus	0.25
Total Potassium	0.20
Calcium	3.0
Magnesium	0.3

7.8.2 Tvoical Oraanic Matter Content - 30%

7.8.3 Tvpical Carbon: Nitroaen (C/N Ratio) - 22

7.8.4 Salinity (chloride, fluoride, sulphate)

Total Salts (milliSiemens/cm) - < 3.5

Sodium Absorption Ratio (SAR) - < 5

7.8.5 pH 5.5 - 8.5

7.8.6 Moisture Content - Commensurate with end-use.
Typically, 30% - 55%

7.8.7 Water Holding Capacity - typically 3 times Dry Weight

8.0 MONITORING

8.1 Introduction

To ensure that the composting operation 'maintains the ongoing quality needed, periodic analysis, monitoring and reporting is required.

The facility operator must retain proof that the compost meets all quality parameters.

The specific sampling and analysis program must be shown in the facility approval.

Operating and production records must be kept two years past the disposition of the compost, and will be made available to the MOE on request, and summarized for the MOE in an annual report.

8.2 Sampling

8.2.1 Sample Size

Grab samples will be taken and cornposited as shown below, for subsequent chemical analyses.

Volume of Cornposited Sample (cubic meters)	Number of Grab Samples Reauired
10	4
15	5
25	6
35	7
50	8
70	9
100	10

(NOTE: 1 Cubic Meter approximates 1 Tonne)

The cornposited sample will represent one day's compost production in the case of a continuous process, or one batch in the case of batch processes. The grab samples will be taken at uniform intervals throughout the working day for continuous processes or from diverse points in the batch (1 meter into the pile from the surface of the pile).

8.2.2 Sampling Frequency

1. Feed Material: When raw feed material quality appears relatively constant, sampling and analysis should be done weekly during the first month. Subsequently, sampling may be done once every two months if consistency is demonstrated.

2. Finished Compost: A composite sample of the compost will be analyzed for guideline compliance every two months or every 5,000 tonnes of compost, whichever comes first. Sampling may be reduced to once every four months if compost quality is demonstrated to be sufficiently consistent on an ongoing basis.

8.2.3 Sample Analysis

Sampling and analysis required by these guidelines, are the responsibility of the facility owner or operator.

Submission of duplicate samples to an MOE designated laboratory for quality control auditing purposes may be required.

8.2.4 Sample Parameters

The MOE may vary the number of parameters to be analyzed for, or the frequency of analysis commensurate with changes in the waste stream or processing, or the known presence of potentially toxic substances.

8.2.5 Sample Quality Assurance

Sample collection, preservation, and analysis will assure valid and representative results pursuant to a MOE-approved quality assurance plan.

8.3 Reporting

Plant owners or operators must, from start-up, record and keep the-following information regarding their activities for a two-year period:

- the type and quantity of wastes received;
- process operating information (temperature, oxygen levels, retention time) and any significant operating problems;
- the quantity, by weight and volume of compost and residues produced and the quantity of compost and residues removed from the facility;
- a description of compost distribution/markets;
- all information and analyses required with copies of laboratory reports and other supporting documentation.

This information will be available to the MOE upon request.

8.4 Monitorins to Assess Off-site Impacts

The impact of composting operations upon nearby property may require monitoring. The need for monitoring will be reviewed, on a case-by-case basis, by MOE Regional staff. The principal concerns are noise, odours, air quality, ground and surface water quality, -vectors and the potential for and effects of liquid discharges to municipal sewers.

The effects of transporting materials to and away from the site, are normally accounted for prior to issuance of the Certificate of Approval. However, monitoring to assess if actual traffic volumes and their effects exceed those predictions may also be necessary.

APPENDIX 1
Derivation of Guideline Criteria

and List of Reference Documents

The Compost Quality Specifications metals criteria were taken from the MOE "Upper Limit of Normal" Contaminant Guidelines for Phytotoxicity Samples, and are the concentrations shown in that Guideline for rural soil.

Total salts and Sodium Absorption Ratio limits were taken from Table A-2 of the MOE Guidelines for the Decommissioning and Cleanup of Sites in Ontario.

Mineral content, pH, organic matter content, carbon to nitrogen ratio, moisture content, and water holding capacity are included showing "typical concentrations". It is deemed that their concentrations will be driven and determined by end user markets'. The Guideline does not attempt to be inappropriately restrictive by limiting concentrations of these parameters.

PCB concentration is taken from the Canadian Council of Ministers of the Environment guidelines for agricultural soils. Inerts concentrations and compost particle size requirements are based on past MOE experience and expectations of raw waste quality, as well as providing guidance in an area where specific market constraints are likely to be more restrictive than concern from an environmental perspective.

There is no single, conclusive or definitive method of quantifying compost stability. For that reason, considerable latitude in selecting stability test is granted proponents, but with the proviso that should such tests not be conducted, then extensive product curing periods must be applied.

Some documents consulted in the preparation of the Guideline include:

Ontario's Guidelines for Sewage Sludge Utilization on Agricultural Lands, developed by the Ontario Ministries of Agriculture and Food, Environment, and Health.

Ontario MOE "Upper Limit of Normal" Contaminant Guidelines for Phytotoxicology Samples prepared by the MOE Air Resources Branch.

Guidelines for the Decommissioning and Cleanup of Sites in Ontario prepared by the MOE Waste Management Branch.

Canadian Council of Ministers of the Environment - PCB Guideline.

Guidelines for Land use Surrounding Small and Medium Sized Sewage Treatment Plants prepared by MOE.

Composting - A Literature Study prepared for MOE, Waste Management Branch.

Florida Dept. of Environmental Regulation, Rule 17-709, "Criteria for the Production and Use of Compost Made from Solid waste".

Minnesota Pollution Control Agency, Solid Waste Management Rule 7001.3375; "Final Application Information Requirements for Compost Facilities".

New York State Dept. of Environmental Conservation, Solid Waste Facilities Sub-Part 360-5; "Composting Facilities".

Fertilizers Act Agricultural Canada, Food Production and Inspection Branch, Fertilizer Section: Memorandum T-4-93 re: "Metal Concentrations in Processed Sewage and Byproducts".

Various Ontario Acts and Regulations have an impact on composting operations. In the Guideline, the use of the Ontario Water Resources Act, the Environmental Protection Act, and the Environmental Assessment Act, administered by the MOE, are outlined where appropriate. Other legislation such as the Consolidated Hearings Act, the Ontario Municipal Board Act, the Planning Act, the Expropriations Act, and the Federal Fertilizers Act may apply in some situations.

In addition, other legislation administered by municipal, provincial or federal agencies may apply, and compliance with the Guideline does not exempt a composting proponent from these. It is likely, however, that use of the Guideline will assist in meeting the legislative requirements of other agencies and help expedite projects.

APPENDIX 2.

PLANT OPERATING INFORMATION

COMMENT: This Appendix describes information which will likely be required when applying for Permit by Rule or EPA Part V Approvals.

Operational Procedures

1. Schedule of operation, showing days and hours that the facility will operate,. preparations for daily opening, daily 'procedures, and procedures followed after closing for the day.

2. Estimated daily traffic to and from the facility, including number of trips by private or public vehicles, routes followed, and quantities of material contained in each vehicle.

3. Description of gate control and incoming material monitoring methods.

4. Procedure for unloading trucks, including frequency, rate and method.

5. Procedures for handling and storing materials for processing, and removal of surplus or non-processible residue.

6. Special precautions or procedures for operation during wind, heavy rain, snow, freezing weather, and other inclement conditions.

7. Finished compost:

    i) a description of the primary markets for the compost;

    ii) method for removal from the site;

    iii) a plan for disposal or other use of compost that cannot meet primary markets due to poor quality or other factors;

    iv) description of label or other information means that outlines:

the type of waste the compost was derived from;

a list of any restrictions on use;

recommended application rates.
(Note that application rates to agricultural land shall not cause the metals concentrations in Column 3 of Table 2 of the Sewage Sludge Utilization Guidelines to be exceeded. The Sludge Utilization Committee of the MOE and OMAF should be consulted.)

analysis as per criteria in Section 7.0 of the Guideline.

Facility Design Description:

Process Equipment

1. Process flow diagram(s) for the entire process, showing all major equipment and flow streams. The flow streams must indicate quantity of the material on a:

   wet weight

   dry weight

   volumetric basis.

2. The type and capacity of equipment, and associated detention time for the handling, processing and storage;

   detailed engineering plans and specifications for the entire facility, including manufacturer's performance data for major equipment;

3. The method of measuring, processing, mixing, and proportioning input materials;

4. A description and sizing (where applicable) of the storage facilities for amendment, bulking agent, raw solid waste, and finished compost;

5. The separation, processing, storage, and ultimate disposal of non-compostable materials (if applicable);

Feedstocks:

1. A detailed description of the source, quality and quantity

of the solid waste to be composted;

- including the source, quality and expected quantity of bulking- agents or amendments (if applicable); and
- the expected recycle rate of bulking agent or compost.

2. The description must include

   - the annual solid waste input (both present and projected)

   - any seasonal variations in the solid waste type and quantity.

3. A description of any additives including quantity, quality, and frequency of use.

Operating Conditions:

1. The location of all temperature, oxygen and any other monitoring points, and the frequency of monitoring.

2. A description of how the temperature monitoring and control system will ensure that the facility will meet pathogen reduction limitations as per Section 6.

3. The aeration capacity of the system and the method of supplying air (air injection and/or method of turning or mixing), monitoring oxygen levels, and controlling air flow.

4. If applicable, a description of the air emission control techniques.

5. The length of the composting stabilization period for each stage of cornposting (if applicable), and the method(s) of measuring stability.

6. Method of controlling inerts (i.e. plastic, glass) in terms of particle size and quantity.

7. A description of methods to collect and control surface water run-off and leachate, including method for treatment or disposal of leachate generated; (for uncovered sites, calculations of surface run-off that must be handled at the site, based on rainfall intensity of one-hour duration).

8. Contingency plans detailing corrective or remedial action

to be taken in event of:

- equipment breakdown
- air pollution (odours)
- unacceptable waste delivered to the facility
- groundwater contamination
- spills

9. The number of staff and their responsibilities.

10. The names of owners, operators or lessees.

11. For facilities subject to EPA Part V Approvals, posting of financial assurance to cover the cost of removing all raw and processed material from site in the event, for example, of bankruptcy. The level of financial assurance can be identified by reference to MOE Policy 02-03. In the case of facilities operating under Permit by Rule, a performance bond must be obtained to address the above, and be re-evaluated annually and the amount adjusted to reflect increased costs.

APPENDIX 3

OVERVIEW OF THE AEROBIC COMPOSTING PROCESS

Aerobic cornposting is a biological decomposition process which reduces complex organic matter into simpler, more stable chemical compounds with the release of heat, water vapour and carbon dioxide. The released heat can, with proper controls, inactivate pathogens and weed seeds. The major requirements for cornposting are: proper process and equipment design; temperature and moisture control; adequate oxygen supply; suitable feed and nutrients to maintain the biological process.

In addition to having no active pathogens, compost should be chemically stable, contain low concentrations of contaminants such as heavy metals and hazardous organic chemicals, and have an earthy, non-offensive odour. It should also retain water, have proper pH and salinity levels and contain enough nutrients (N, P, K) to benefit plant growth without having adverse effects on soil.

Cornposting is a multi-phased process:

- Phase I - Collection and preparation of the raw material
- Phase II - High rate biological degradation
- -Phase III - Curing
- Phase IV - Grading of the final product
- Phase V - Storage, marketing, transportation and use.

Raw materials with potential for cornposting are:

- the biodegradable organic fraction of municipal solid waste
- yard, garden, grass and leaf wastes;
- agricultural crop residues and animal manures;
- food processing wastes;
- forest products and paper production wastes;
- sludges from sewage treatment plants.

The collection and transportation methods used are an integral part of any cornposting operation. Source separation of the collected materials greatly reduces contaminants entering the cornposting process.

Waste pretreatment to reduce particle size is generally necessary. This can be accomplished using shredders, grinders or hammermills with suitable screens to produce a fine, homogenous material for composting. Hammermills are particularly effective in pulverizing brittle materials into granules instead of splinters or shards. Ferrous metals can be removed by magnets.

Generic Methods of Composting

Composting process technologies fall into three main categories. Each category has its own aeration method:

- windrows (turned or static)
- aerated static pile
- in-vessel

Turned and Static Windrows

Raw material is stacked into an elongated pile of approximately triangular, cross-section shape.

Windrows are torn down and reconstructed by mechanical turning. The method and frequency of turning is closely related to the nature of the waste, its oxygen demand, moisture content, uniformity of decomposition, structural strength and pathogen inactivation requirements.

In turning, the outside layer of the original windrow becomes the interior of the rebuilt windrow. Multiple turnings lend more assurance that proper cornposting process conditions are met.

Turning should be done in relatively calm weather to minimize off-site effects due to odours or dust.

Static windrows (windrows that are not turned) rely on the natural diffusion of oxygen into the pile, and are unlikely to provide conditions to allow compost to meet this Guideline.

Aerated Static Pile

The aerated static pile method features either forced (injected) air into the composting mass, or drawn (inducted) air through it, or both. Static piles are sometimes turned mechanically.

To construct a static pile windrow, a grid of perforated pipe is laid. The grid is connected to a fan .and is covered with a layer of bulking agent (e.g. wood chips) or finished compost. The compost pile is then built on the grid. The pile remains intact (i.e. static) throughout the cornposting period, and-is topped with a layer of finished compost to provide insulation to ensure the adequate temperatures for pathogen destruction.

In-Vessel

There are several types of in-vessel systems:
- Rotating drum
- Horizontal (rectangular/cylindrical) or Vertical (silo)
- Channel

The objective of these systems is to optimize aeration, temperature and moisture conditions, through improved mixing and automated process control and monitoring systems.

MAJOR OPERATING PARAMETERS

The Staaes of Composting

Cornposting generally occurs in two stages. Initially, the reaction is characterized by high temperature, high oxygen uptake rate, rapid bio-degradation of organic solids, and a high potential for odour production.

As the reaction progresses and waste is consumed, biological activity slows, and as a result the temperature declines. This second stage allows curing, where some residual biological activity occurs. It ends when the residue reaches the required stability. In this stage, temperature, oxygen uptake rate, and potential for odour production are lower.

Stabilitv

There is no exact definition of biological stability with respect to cornposting. Stability is proportional to retention time, under proper operating conditions, and waste characteristics. The degree of stability required may depend on the end-use of the compost. Complete-stability is-not-readily attainable and not likely desirable as there would be no soil amendment value due to low or non-existent organic content.

On the other hand, compost with a high potential for continuing decomposition can adversely affect crop growth due to toxic effects and nitrogen depletions. There is, therefore, a level of stability which must be met based on end-use of product, and the ability of the compost to be stored or handled with no nuisance effects or conditions occurring.

The relative stability can be determined using indicators such as volatile solids destruction, spontaneous heating, oxygen uptake rates, toxin production, carbon to nitrogen ratio; seed germination and growth tests and redox potential. These tests are not necessarily conclusive or definitive, but do indicate relative stability of compost, compared with the raw feed.

Temperature

The initial ambient temperature of a cornposting mass quickly reaches thermophilic temperature due to the highly exothermic nature of the biological reaction. Eventually, as biological activity diminishes due to reduction of feed concentrations, the temperature returns to ambient levels during curing.

It is important for the composting mass to attain a temperature between 55° C and 60° C for some time to inactivate pathogens in the material.

Biological activity can continue beyond 60° C, but will be impaired as the bacteria will suffer inhibition. At temperatures approaching 80° C, all activity will cease. It should be cautioned that substantial drops in temoerature can be caused by effects such as oxygen deficiency, low moisture levels, thermal kill of micro-organisms, or toxic effects due to contaminants.

Aeration

Aeration maintains aerobic conditions for the micro-organisms and inhibits the formation of anoxic or anaerobic conditions and resultant odours. Aeration must also satisfy the demands of temperature control, and moisture removal. Determination of air requirements is complex and dependent on both biological and physical variables.
Different wastes will exhibit different oxygen demands. Aeration rates are therefore specific to the chemical and physical character of the waste to be composted, and should be determined during the design stage.

Moisture

The micro-organisms require an aqueous, or moist environment to effectively biodegrade wastes. Moisture content, temperature and aeration are closely related. As moisture evaporates, the reaction slows, the temperature drops below the required level, and the process is inhibited. Subsequent addition of moisture will increase the reaction rate to previous levels and the process will continue.

Carbon to Nitroaen Ratio (C/N)

Control of the C/N ratio is important in optimizing the biological decomposition. The micro-organisms use carbon as a source of energy and nitrogen for building cell structure. The C/N ratio declines as the decomposition process proceeds. The-final compost C/N value affects soil and plants when the compost is applied.

The cornposting reaction is inhibited at C/N ratios greater than 25/1, due to lack of nitrogen. If high C/N compost is added to soil, soil micro-organisms compete with crops for available nitrogen, thereby reducing growth.

At compost C/N ratios lower than 20/1, the energy source (carbon) is less than needed for conversion of nitrogen into proteins. Such material added to soil would result in the soil microbes removing the excess nitrogen as ammonia, denying it to plants.

High C/N ratios can be lowered by adding nitrogenous waste (e.g. grass clippings, green vegetation, non-ruminant animal manure). A low C/N ratio can be increased by adding low nitrogenous, high carbonaceous waste (e.g. hay, dry leaves, chopped twigs).

Nutrient Content

Carbon(C) and nitrogen(N), as well as phosphorous (P) and potassium (K), are macronutrients for micro-organisms. Micronutrients include cobalt (Co), manganese (Mn), magnesium- (Mg), copper (Cu) and calcium (Ca). The latter serves as a buffer that resists changes in pH.

with the exception of C and N, most organic wastes contain adequate amounts of nutrients for cornposting.

Particle Size

Aeration, moisture content, and particle size affect access of micro-organisms to food and nutrients. There is a balance between the desirability of minimal particle size for a more rapid reaction and the need for porosity, created by larger particles, for air, moisture and nutrient flow interaction throughout the pile.

Hvdroaen Ton Level (pH)

The optimum pH range for composting is 5.5 - 8.5. Typically, pH levels drop when composting begins, then gradually rise a s the reaction progresses.

Salinitv

Typically, composts contain about 1% - 2% of soluble salts. These are principally the chlorides and sulphates of alkaline metals. The amount of other acids, including organic acids, depends on the specific process and waste.

When compost is used, some of the salts are taken up by the plants, some remain in the soil and others may leach into the groundwater.
Plants vary in their sensitivity to salt. Excessively high levels of salt in soil adversely affect root function and plant growth. Seedlings and newly rooted cuttings are particularly sensitive.

Pathoaens

Pathogenic organisms, present in various organic materials, are a potential public health threat to site operators and compost users. Pathogens belong to four main groups: bacteria, viruses, parasites and fungi. In composting, heat is the primary factor in pathogen inactivation.

Thermophilic temperatures must be reached and-maintained for an adequate time to inactivate pathogens effectively.

Water Retention

Compost must have the ability to retain water and air in soil to which it is added.

Health and Safetv Issues

iiealth and safety issues are administered through the Ministry of Labour's Occupational Health and Safetv Act, and its Reaulations for Industrial Establishments.

In composting facilities, particular care must be placed in conforming with requirements for "confined spaces" in the above regulations, as there is a high potential for oxygen depleted atmospheres in and around composting vessels or masses.

Composting is a biological process analogous to sewage treatment, and regular inoculation of employees may be required, similar to programs for sewage treatment workers. Safeguards against dust inhalation are also important due to the potential for an appreciable endotoxin content in compost plant dust.

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APPENDIX D

The Potential for Reductive Dissolution of Fe(III)-Oxide Minerals and the Subsequent Release of Dissolved Metals in Weathered Tailings Covered With Composted Landfill Materials

The Potential for Reductive Dissolution of Fe(III)-Oxide Minerals and the Subsequent Release of Dissolved Metals in Weathered Tailings covered with Composted Landfill Materials

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INTRODUCTION

Most metal-mine mill-tailings impoundments contain sulphide minerals. The most ahundanr of these minerals are the ferrous sulphide minerals pyrite (FeS_2) and pyrrhotite ($Fe_{(1-x)}S$). When exposed to water and oxygen, these sulphide minerals oxidize readily through reactions of the form:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightleftharpoons Fe^{2+} + 2SO_4^{2-} + 2H^+$$

At many locations, water in contact with oxidizingsulphide minerals in inactivemine tailings impoundments is acidic and contains high concentrations of dissolved SO,, Fe(II), and other metals including Cd, Co, Cr, Cu, Mn, Ni, Pb, and Zn and metalloids including As, Sb, and Se (Blair et al., 1981; Dubrovsky et al., 1984a, b; Blowes and Jambor, 1990). Rainfall and snowmelt water displaces these metal-containing waters downward through the tailings and ultimately towards surface water flow systems (Dubrovsky et al., 1984b). If released untreated, these tailings-derived waters can be detrimental to the health of plants, wildlife, and fish (Feasby et al., 1991).

One approach to the remediation of acidic drainage is by covering the tailings with various materials, to isolate the sulphide minerals from water and/or oxygen. Among several possible covers (for example, revegetation, wet barriers, dry covers), using an organic cover composed of sewage sludge, sawdust, compost, or peat, seems to be long-term effective and an inexpensive alternative (Broman et al. , 199 1; Blenkinsopp et al., 1991; Brown, 1991; Pitchel and Dick, 1991).

The principal benefit of organic covers is that oxygen is consumed in the upper part of the organic materials by aerobic bacteria, maintaining anaerobic conditions in the tailings. Thus, the oxidation of the sulphide minerals by atmospheric oxygen is prevented. Moreover, Pitchel and Dick (1991) have noticed that some organic compounds produced by the cover inhibit the activity of *T. Thiooxidans* and *T. Ferrooxidans*, which normally catalyze the oxidation of sulphide minerals.

Although organic covers seem to prevent acidic drainage in mine tailings. it is necessary to assess the magnitude of the potential geochemical problems that may be associated with these covers, particularly those concerning the reductive dissolution of ferric oxides, which are very abundant in oxidized tailings. Reductive dissolution can occur in two different ways under anaerobic conditions: first by purely chemical reaction of iron(III) oxides with organic compounds leaching from the cover and secondly by reaction involving bacteria which use iron(III) oxides as an electron acceptor during their metabolism.

The consequences of the reductive dissolution of ferric oxides may be particularly significant in oxidized tailings environments where trace metals contained in the oxides and hydroxide minerals in the vadose zone may be released to the water during reductive dissolution (LaKind and Stone. 1989; Sulzberger et al., 1990; Lovley and Phillips, 1986). In addition, the porewater concentrations in Fe^{2+} may increase dramatically in the shallow vadose zone where sulphide oxidation is complete. This Fe^{2+}, carried by infiltration waters would eventually reach an oxygen source and thus be oxidized, leading to the regeneration of acidic conditions.

1. Reductive Dissolution of Iron(III) Oxides bv Organic Comwunds Derived from Composted Municipal Landfill Wastes

1 Organic compounds in landfill leachates

The organic compounds most likely to chemically reduce the ferric oxides in the tailings are those components of the leachate derived from the organic cover above the tailings. Unfortunately, there is very little information available concerning compositions of organic leachates in the literature, because authors usually deal only with hazardous organic contaminants contained in landfill leachates. The concentrations of these hazardous compounds are very low, and they are not common to any organic leachate.

Baedecker and Back (1979), however, give the composition of a landfill leachate and determined the concentrations of the eight lowest molecular weight organic acids from a landfill:

acetic	50.4 mg/l
propionic	50.8 mg/l
isobutyric	25.8 mg/l
butyric	132.9 mg/l
isovaleric	72.1 mg/l
valeric	5 1.4 mg/l
isocaproic	10.7 mg/l
caproic	75.7 mg/l

These volatile fatty acids are widely recognized as contributing the most important part of landfill leachates (for example, Barlaz et al., 1989; Robinson and Maris, 1979). These volatile fatty acids, mainly acetate, propionate, and n-butyrate, may even account for up to 90% of the organic matter in leachates from young landfills (Gourdon et al., 1989).

Hazardous organic compounds likely to be detected in landfill leachates were determined by Reinhard et al. (1984), who identified a lot of components such as aliphatic and aromatic acids, phenols, resin acids, and terpene compounds in field experiments.

Additional useful information about landfill leachates is given by Schuk and James (1986). They used an artificial landfill leachate solution whose composition is:

Chemical	Formula	Amount (kg)	
sodium acetate	CH_3COONa	18.6	(dilute chemicals to 568 L
glycine	NH_2CH_2COOH	8.6	with fresh tap water)
acetic acid	CH_3COOH	13.6	
propionic acid	CH_3CH_2COOH	16.8	
salicylic acid	$2\text{-}HOC_6H_4COOH$	2.3	

This composition is similar to that observed by Baedeker and -Bach (1979) in that acetic and propionic acids are the most abundant fatty acids in the synthetic landfill leachate. Further information is required about the composition of other leachates (sawdust, peat, compost, sewage, etc.). As Pichtel and Dick (1990) noted different rates of reaction with different organic materials used for the amendment of mine spoil and attributed these differences to variations in the composition of the leachates. we cannot assume that leachate composition is always the same.

2. Reductive dissolution of iron(III) oxides by organic compounds - Laboratory experiments

The literature documents several experiments of oxide dissolution by organic compounds. These experiments include the following combinations of oxide minerals and organic compounds:

Oxides	Organic Compounds	Author(s)
goethite (and other iron oxides)	oxalate	Zinder et al. (1986)
hematite and goethite	oxalic acid	Suter et al. (1988)
magnetite and hematite	ascorbate	Dos Santos Alfonso et al.
goethite and hematite	phenolic reductants (catechol, hydroquinone, benzoic acids)	LaKind and Stone (1989)
manganese(III) and (IV) oxides	hydroquinone	Stone and Morgan (1984a)
manganese(III) and (IV) oxides	27 aromatic and non-aromatic compounds	Stone and Morgan (1984b)
manganese(III) and (IV) oxides	substituted phenols	Stone (1987a)
manganese(III) and (IV) oxides	oxalate and pyruvate	Stone (1987h)
manganese(N) dioxide and	hydroquinone	Stone and Ulrich (1989)

These studies have important implications with respect to the effects of organic leachates on oxidized tailings which contain an abundance of iron(III) oxides. Some reductive dissolution experiments have indeed been carried out using oxidized-metal minerals (particularly Mn(III) and Mn(IV) oxides) and low molecular weight volatile fatty acids (Stone, 1987b), which constitute the most important fraction of landfill leachates. Several experiments were also conducted using oxide minerals and phenolic compounds (LaKind and Stone.

1989), which are also present in landfill leachates. Moreover, humic and fulvic acids contained in landfills also have a reductive capacity which allow them to dissolve these metal oxides (LaKind and Stone, 1989)

The experiments describing the dissolution of Mn or Co oxides are also interesting and may be directly useful because many weathered mine tailings contain Mn oxide minerals (Blowes and Jambor, 1990). Moreover, Stone and Ulrich (1989) compared the rates of reductive dissolution of Mn or Co oxides with those of Fe(III) oxides, and observed that, at low pH levels, Fe(III) oxides participate in the same reactions as Mn or Co oxides, although Fe oxides are weaker oxidants. Thus, we may expect that the organic compounds which have been found to be able to oxidize Mn or Co oxides also may he able to oxidize some of the various iron(III) oxides, at least under acidic conditions.

Dos Santos Alfonso et al. (1989) state that all organic matter is thermodynamically able to reduce Fe(III) whereas Stone and Ulrich (1989) say it is thermodynamically possible only below pH = 3.25. On the other hand, Lovely (1987) affirms that the chemical reduction of Fe(III) by organic compounds probably is not a quantitatively significant process in most environments.

Lastly, among the various iron(III) oxides studied, some are more likely than others to be reduced by organic compounds. For example, LaKind and Stone (1989) noted that goethite undergoes reductive dissolution more quickly than hematite. Generally, all authors who study the reductive dissolution of iron(III) oxides (either by organic compounds or by bacteria) agree that the less well-crystallized the ferric oxide. the more rapid its dissolution (for example, see Lovley and Phillips, 1986).

The results of these experiments suggest that abiotic reduction of metal-oxide and hydroxide minerals is possible and that the least crystalline of the ferric oxyhydroxide minerals, those which are most abundant in recently oxidized tailings, are more susceptible to reductive dissolution than the more crystalline minerals.

II. Reductive Dissolution of Iron(III) Oxides by Bacteria

I. Bacterial pathways of ferric oxide reduction

The iron(III) oxides in natural environments can he reduced either directly or indirectly by bacteria (LaKind and Stone, 1989). Bacteria can participate directly in the reductive dissolution reaction hy using membrane-bound electron transfer proteins to couple intercellular redox transfer process to extracelluar iron reduction, they can also participate indirectly by allowing biologically refractory compounds to accumulate and by excreting metabolites and other compounds that have reductive properties. In the first case, Arnold et al. (1986), Lovley (1987) or Jones et al. (1983) emphasize that because of the low solubility of Fe(III), organisms may have to come into direct contact with Fe(III) to reduce it.

The second case is theoretically the same as the one discussed in the previous section (chemical reduction of ferric oxides by organic compounds), but we may not be able to know all the organic compounds (metabolites) produced by bacteria under the conditions we are interested in.

We have also to distinguish between two sorts of bacteria: bacteria contained in the tailings. and bacteria contained in the organic cover materials. Depending on the nature of the bacteria and on its way of action (direct or indirect), the extent of the reduction dissolution in the railings may be different.

Thus, the four possible cases are the following:

	Direct participation of bacteria in dissolution. Fe(III) is electron acceptor. Physical contact with the cells is required.	Indirect participation of bacteria in dissolution. The reaction is only chemically induced.
Bacteria are contained in the tailings.	The reductive dissolution will occur in all the parts of the tailings which contain enough bacteria, sufficient organic carbon and oxide minerals.	The reductive dissolution can occur in the entire tailings impoundment when organic carbon is present
Bacteria are contained in the organic cover only.	The reductive dissolution will probably he more important at the boundary tailings/cover.	The reductive dissolution will occur in the part of the tailings reached by the leachates.

2. The iron(III) reducing bacteria

In his review, Lovley (1987) gives many examples of microorganisms that reduce Fe(III). These bacteria include *Pseudomonas sp.* 200 (Arnold et al., 1986), a member of the genus *Vibrio* (Jones et al.. 1982), *Alteromonas putrefaciens* (Lovley et al., 1988), and the microorganism GS-15. identified by Lovley and Phillips (1988), which completely oxidizes organic matter to carbon dioxide with the reduction of Fe(III) or Mn(IV). Several of these bacteria, including *Pseudomonas@*. are common in a variety of natural systems. In addition, a variety of organic compounds can serve as electron donors for this redox reactions: acetate, propionate, butyrate, formate, Iacetate, ethanol (Lovley and Phillips, 1988, 1989), aromatic compounds (Lovely et al., 1989), toluene, phenol, and p-cresol (Lovley and Lonergan, 1990). Many of these organic carbon compounds were identified as common components of landfill leachates. Thus, it seems possible that these metal-oxide-reducing microorganisms will be able to become established in tailings covered with various organic materials. And, there is a possibility that Fe(III) oxides may be biologically reduced.

Consideringthesusceptibilityofthedifferent forms of iron(III) oxides to bacterial reduction. Lovley (1987) indicates that, as for abiotic reduction, the less crystalline the Fe(III) form, the more readily it is microbially reduced, and quotes the following sequence from Ottow (1969): $FePO_4 \cdot 4H_2O$ (most easily reduced) > $Fe(OH)_3$ > $\gamma FeOOH$ > $\alpha FeOOH$ > Fe_2O_3. On the other hand, less crystalline Fe(III) forms can be reduced by “weaker” organic compounds.

III. Release of Trace Metals Through Reductive Dissolution

1. Trace metals contained in iron(III) oxides

Tessier et al. (1984) review many studies of trace metal adsorption onto iron oxyhydroxides and slow using a sequential extraction procedure (Tessier et al., 1979) that cadmium. copper. nickel. lead. and zinc may beadsorbed onto ferricoxides. Moreover, experimental results reported hy Belzile and Tessier

(1989) suggest that arsenic is largely associated with Fe oxyhydroxides in oxic sediments and is released in the interstitial water when Fe(III) is reduced to Fe(II).

The iron(III) oxides present in the tailings contain several adsorbed and coprecipitated trace metals (Blowes and Jambor, 1990; Blowes et al., 199 1; Jambor and Blowes, 199 I). These metals are susceptible to release by reductivedissolutionof ferric oxyhydroxide minerals. Under the reduced conditions that would prevail below the anaerobic cover, readsorption of these metals onto Fe(III) oxides is unlikely and their transport may be enhanced.

2. Sequential extraction procedure

The amount of trace metal likely to be released during the reductive dissolution of tailings minerals can be determined by the sequential extraction procedure for the speciation of trace metals described hy Tessieretal. (1979)and later by Tessier et al. (1989). Theyhavedevelopedananalyticalprocedureinvolving sequential chemical extraction for the partitioning of trace metals into six fractions:

Fraction 1: exchangeable trace metals;

Fraction 2: trace metals bound to carbonate or specifically adsorbed;

Fraction 3a: trace metals bound to Mn oxides;

Fraction 3b: trace metals bound to Fe oxides;

Fraction 4: trace metals bound to organic matter and sulphides;

Fraction 5; residual.

3. Reliability of the results

The issue of the significance of the sequential extraction results is the purpose of several papers, among them, Tessier and Campbell (1988), Belzile et al. (1989), Nivel and Morel (1990), and Tessier and Campbell (1990). The arguments against this procedure are the following: problem of readsorption of trace metals during the extraction, absence of validation by laboratory experiments conducted with well-defined samples, results which are "operationally defined", and physicochemical conditions used during extraction procedures very different from naturally-occurring processes. Against that is objected that the choice of samples or reagents in the laboratory experiments supposed to invalidate the sequential extraction procedures can be seriously questioned.

However, we are allowed to assume that the results of the sequential extraction procedure are an upper limit and that, under naturally-occurring condition, with weaker reagents and slower kinetics, the amount of metal released would be less important.

CONCLUSIONS

1. The most common derivatives of organic carbon sources contained in municipal landfill leachates are the fatty organic acids including acetate and propionate. These same compounds may be associated with composted municipal landfill materials.
2. Reductive dissolution of metal-oxide minerals can occur either abiotically or through biologically-mediated reactions. In general, the metal oxides with the greatest electrochemical potential are those most susceptible to reductive dissolution, following the order Mn(III, IV) oxides > Co(III) oxides > Fe(III) oxides.
3. Although thermodynamically favoured abiotic reductive dissolution of Fe(III) oxides by landtillderived shortchainorganic acids is likely to be slow. Biologically catalysed reduction using the same organic acids is expected to be much more rapid.
4. Field studies, conducted at inactive, weathered mill tailings impoundments indicate that many of the metals released through sulphideoxidation in the vadose zone of inactive tailings impoundments

are retained in theshallowtailings by adsorptionor coprecipitation with Fe(III) oxide and hydroxide precipitates.

5. Reduction of Fe(III) oxides by organic acids has been observed to result in the release of trace elements to porewaters. Similar release of trace elements in weathered tailings impoundments may be anticipated.

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APPENDIX E

Metropolitan Toronto Solid Waste Master Plan • Synopsis

SOLID WASTE MANAGEMENT MASTER PLAN

MASTER PLAN SYNOPSIS

INTRODUCTION:

Through the Solid Waste Environmental Assessment Plan (SWEAP) process, the Metro Toronto Works Department has completed a draft Solid Waste Management Master Plan Strategy **report.** The report describes how Metro's solid waste is managed now and for the next 40 years.

GENERAL PRINCIPLES:

To develop a Master Plan that addresses legislative requirements and reflects the needs and desires of the community, Metro will:

- Establish a solid waste management system *in* a technically, socially, culturally, environmentally, financially and economically acceptable manner.

- Establish the necessary programs and facilities to divert from disposal a minimum of 25 percent by the year 1992 and 60 percent by the year 2000 of the total solid waste generated.

- Achieve the above diversion targets, to the extent possible within its jurisdiction, through the following hierarchy of waste management methods, in order of priority:

  1. Reduce the quantity of material becoming solid waste;
  2. Reuse material in its original form:
  3. Recycle material into new marketable products;
  4. Compost organic material: and
  5. Landfill or incinerate with energy recovery (if allowed by the Province.)

- Achieve to the extent possible, progress up the above hierarchy of waste management methods.

- Look first within its own boundaries to site its waste management facilities and, if necessary, within the remainder of the Province of Ontario.

- Ensure that the policies are implemented in a manner that allows for public participation.

- Provide the basis for the management of solid waste for a 40-year planning period and ensure that adequate facilities are approved and available as required.

- Establish a solid waste management system that is flexible and has adequate back-up potential.

PROPOSED WASTE MANAGEMENT PROGRAMS:

The draft Master Plan Strategy report recommends a number of 3Rs and composting programs that will help us reach our long-term goal of 90 percent diversion by 2030. The following are just a few of these programs.

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REDUCTION

Reduction Is the most important of the 3Rs. By not producing the waste in the first place, we eliminate the need for reuse, recycling and disposal.

Master Plan Recommendations

Ban from disposal, by 2000, all packaging which is not reusable or recyclable.

Enhance public education programs to promote the 3Rs.

Provide technical assistance to the Industrial/Commercial/Institutional (ICI) sector to start or Improve their waste reduction programs.

REUSE

Reusing an item can greatly extend its life and does not require the resources and energy of recycling or disposal.

Master Plan Recommendations

Establish up to six Material Exchange Facilities where used materials will be collected from, and offered to, the public.

- Support the used material collection efforts of charitable organizations.

RECYCLING

Until reduction and reuse practices Improve, recycling programs will continue to play an Important role. By the end of 1992, residents will be able to recycle more materials through the Blue Box; more Blue Domes will be placed In public areas; and all apartments or townhouse complexes will receive recycling collection.

Master Plan Recommendations

- Construct up to six Materials Recovery Facilities (MRFs) by 2000, and a seventh by 2030. MRFs will accept recyclable materials for sorting and preparing for recycling markets.
- Develop new markets for recyclable materials. As these are found, more materials will be banned from disposal facilities.
- Ban, from disposal, all Blue Box materials by 1996 and plastic film, boxboard and mixed paper by 1998.

COMPOSTING

Composting reduces the amount of organic material going to disposal while creating a valuable soil conditioner.

Master Plan Recommendations

Expand the Home Composting Program to allow for the continued distribution of backyard units (350,060 total).

Promote 3-Bin compostlng by residents In apartment buildings and co-ops.

... more

Construct up to four Centralized Composting Facilities by the year 2000. These plants will compost materials from residents, restaurants and commercial sources.

COLLECTION:

With the construction of the new facilities, residents will eventually separate their waste into three streams • recyclables, regular garbage and organics (wet waste).

PUBLIC EDUCATION:

An important component of Metro's waste management program has been, and will continue to be, public education. The draft Master Plan Strategy recommends spending $60 million on public education, to raise awareness about waste management issues and programs; to teach residents and industry how to participate in those programs; and to develop educational and promotional materials to meet the needs of English-speaking and non English-speaking residents of Metro Toronto.

REQUIRED FACILITIES:

The draft Master Plan Strategy recommends the construction of a number of waste management facilities in order to meet Metro's waste diversion targets.

Materials Recovery Facilities

We need the technology of Materials Recovery Facilities (MRFs) to handle the large supply of recyclable materials collected from residents and industry. A MRF is a large industrial type building where a variety of recyclable materials such as household items from the Blue Box or cardboard and wood from the industrial sector are sorted into different categories. The sorting is done by a combination of manual labour and machinery. Sorted materials are then either baled, shredded, crushed or otherwise prepared for market.

The draft Master Plan Strategy recommends the construction of up to six MRFs within the Metropolitan area by the year 2000, and a seventh by 2030. Each facility will be able to accept up to 500 tonnes per day of recyclable materials.

Centralized Composting Facilities

The composting plants recommended would be able to accept up to 500 tonnes per day of different organic materials daily from the residential and the ICI sectors. A Centralized Composting Facility requires a large area (up to 20 acres) and special machinery to prepare and compost the materials In a highly controlled process. There are a number of composting technologies which may be considered for the proposed facilities. These include Windrow Composting, Mechanical Composting and Hybrid Composting.

Metro is currently completing the construction of a small-scale composting plant at the Duffetin Transfer Station in Downsview. The facility will use the In-Vessel method, combined with outdoor curing 'cells'. A pilot collection project will be started this fall to study the potential success of a centralized composting program for Metropolitan Toronto.

SITE SELECTION:

Before Metropolitan Toronto can begin to construct any Materials Recovery Facilities or Centralbed Composting Facilities, a detailed site selection process must take place. The site search will help to identify the best location for each facility. An extensive public consultation program will take place during the site selection process. This will include open houses, public meetings and other events.

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ESTIMATED **COSTS:**

The major costs of the program from 1992 to 2000, are as follows:

6 Materials Recovery Facilities	$180,000,000
4 Centralized Composting Facilities	$140,000,000
Public Education and Communications	$ 60,000,000
Waste Reuse and Recycling Initiatives	$ 15000,000
Three Stream Collection Implementation	$ 15,000,000
Backyard Composters	$ 13,000,000
Household Hazardous Waste Program	$ 20,000,000
Other 3Rs Programs	$ 7,000,000
Site Acauisitlon	$200,000,000
Total	**$650,000,000**

- Assumes costs of $20 million per site.

PUBLIC **CONSULTATION:**

The draft Master Plan Strategy report is the product of Metro Toronto staff, private consultants and public input through the Multistakeholder Committee, SWEAP Caucuses, environmental groups, community associations and private citizens. And the work is not over.

Following the release of the draft Master Plan, there will be a 90-day period of public consultation. The public's role In the review of the Master Plan is very Important. Public support will guarantee the continuation of programs such as Blue Box and backyard cornposting. It will also guarantee a long-term solid waste management plan that reflects the needs and concerns of Metro's citizens.

QUESTIONS?

If you would like more information on the draft Solid Waste Management Master Plan, contact Bob Davis, Assistant Project Facilitator, Public Participation Office, at 392-2990. The Public Participation Office of the Metropolitan Works Department is located at 138 Hamilton Street in Toronto and is open from 8:30 a.m. to 4:30 p.m., Monday to Friday. Every attempt will be made to provide information to residents In their preferred language, in braille, large print *or* talking book format.

SEPTEMBER 1991

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1. INTRODUCTION

Many ore bodies and surrounding waste rock consist of metal sulfides, particularly iron sulfides, pyrite and pyrrhotite. During a mining operation 90% of an ore is typically discarded as tailings after separation by milling and flotation to prepare a concentrate for further processing (Moore and Luoma 1990). The tailings frequently contain a significant amount of sulfides and heavy metals.

When sulfide-bearing mine tailings are exposured to air and water, adjacent surface waters may become contaminated with high levels of acidity and metals. Specifically, formation of acid mine drainage (AMD) is caused by chemical and bacterial oxidation of readily oxidizable iron sulfides with the concomitant formation of sulfuric acid, which in turn leaches heavy metals. In general, metals are readily leached at low pH.

There are approximately 15,000 hectares of acid generating mine wastes in Canada. Since biological communities are greatly affected by AMD there is a compelling need to seek and apply corrective measures. The seriousness and extent of the problem has prompted the mining industry along with the federal and several provincial governments to cooperate in investigations of innovative methods for enduring, environmentally effective management of tailings that would allow mine operators to walk away after mine closure without subsequent long-term active management of the tailings.

This report is a preliminary examination of the feasibility of using the organic waste portion of the non-hazardous -municipal solid waste stream suitably processed as compost to help address the AMD problem. As urban communities find traditional waste disposal methods such as landfill increasingly difficult, they may be persuaded to engage in appropriate collection and large scale composting activities if ensured of securing suitable markets.

Ever increasing amounts of waste have placed a premium on wise land use and environmental planning. The Ontario Ministry of the Environment has decreed that municipalities must divert 50% of their waste from landfill and incineration by means of reduction, recycling and reuse by the year 2000. For the Municipality of Metropolitan Toronto and the Regions of York and Durham, approximately 2 million tonnes of waste must be diverted each year. Many municipalities will have difficulty meeting this target unless creative solutions are found.

This report is the first of two. The first report examines the viability of the concept of compost application to mine tailings from technical, economic and policy perspectives. Although AMD and municipal solid waste problems are national in scope, Ontario is emphasized. Ontario's proposed provincial waste management policies will soon encourage large scale cornposting and the mining industry has initiated several relevant research and reclamation projects in Ontario. The second report will examine wetland reclamation ecology in substantially more detail than is presented here.

1.1 Prevention and Control of Acid Mine Drainage

AMD often exceeds regulatory standards for metal concentrations and pH (low pH is associated with high acidity). The Ontario Provincial Water Quality Objectives (PWQO) for pH, alkalinity, metals and radionuclides are published by the Ontario Ministry of the Environment (Water Management, 1984, Table 1). The acceptable pH range in surface waters is 6.5-U and alkalinity should not be decreased by more then 25% of the natural concentrations for protection of aquatic life. The federal guidelines are similar (Canadian Council of Resource and Environment Ministers 1987). The PWQO are currently under review.

Mitigation of AMD can take the form of treating acidic discharge from tailings impoundments by means of natural attenuation processes in wetlands or by controlled or semi-controlled dosing with neutralizing agents such as calcite, slaked lime or quicklime (Zurbuch 1984, Fraser et al. 1985, Sverdrup et al. 1985).

Dosing is used by Rio Algom at its Elliot Lake tailings sites as well as many other mining companies (Al Vivyurka, personal communication). It is also very common in Scandinavia where sophisticated doser technology has been developed for the treatment of remote streams which are atmospherically acidified. Controlled dosing must be employed as long as exposed tailings continue to generate AMD, which may last centuries beyond the life of the mine, and may produce large volumes of sludge.

AMD can also be controlled and perhaps eliminated by reducing the rate of oxygen supply to sulfide-bearing tailings by means of some type of cover to prevent acid generation although relationships between field conditions and long-term effectiveness have yet to be firmly established. Two tailings reclamation methods appear promising.

Flooding of tailings (i.e. raising the groundwater level and maintaining the surface in a permanently saturated state) where hydrologically feasible may be an effective means of preventing oxygen penetration because the molecular diffusion rate of oxygen in quiescent water is quite low. Hence, flooding is receiving increased attention (Environment Canada 1987; Balins et al 1991). The rate of oxygen diffusion to tailings beneath a wetland could be further lowered by the introduction of an oxygen consuming barrier, such as microbially active organic material, placed between the tailings and sources of oxygen such as aquatic plants and the atmosphere. In natural aquatic systems, thick organic-rich bottom sediments are an effective oxygen consuming barrier.

A second reclamation method utilizes a layer of fine-grained material above coarser material (Nicholson et al. 1991; Yanful 1991). The fine cover material is designed such that it is maintained in a moisture-saturated state regardless of the depth to the water table (i.e. drainage is limited) and therefore minimize exposure of underlying tailings to oxygen. As with flooded tailings, the effectiveness of engineered covers in reducing AMD as well as erosion would be greatly enhanced by the presence of organic material

The central scientific premise of this report is that the rate of AMD formation in an artificial wetland or from tailings with engineered covers will likely be lower when substantial organic sediments are present than in a system lacking substantial organic sediments.

1.2 Creating an Enhanced, Self-Perpetuating Oxygen Barrier

The oxidized zone (zone with oxygen present) of bottom sediments in natural aquatic systems typically does not extend more than 2-4 cm below the sediment/water interface. Sediments below 4 cm are virtually oxygen free. This is because the rate of oxygen consumption by heterotrophic bacteria in surface sediments exceeds the rate of oxygen diffusion into the sediment from surface sources. (Heterotrophic bacteria obtain energy and carbon from the breakdown of organic detritus and are very numerous in sediments.) The rate of **oxygen** consumption in sediments is a function of new organic material derived annually from the activity of the pond's biological communities, which are, in turn, partially dependent on sediments as well as'new inputs of nutrients from external sources each year. Sediments play an important oxygen consuming role in viable, self-sustaining aquatic ecosystems.

In newly flooded tailings (or tailings with moisture-saturated covers) there will be little organic **material.** Therefore, the rate of oxygen supply to the tailings will be limited primarily by the molecular diffusion rate of oxygen through water. Organic sediments will accumulate at a very low rate, even if tolerant vegetation such as the common cattail, Tvpha latifolia, are planted. Also, the rate of successional changes following planting due to invasion by native flora from adjacent wetlands will be slow, although in time a mature, self-sustaining, productive aquatic community would develop (e.g. Brooks 1990).

A thick layer of organic-rich material added to newly flooded tailings or engineered covers would likely promo te aquatic plant productivity and facilitate the creation of a more effective oxygen-consuming sediment barrier. The organic-rich material would provide suitable substrate for bacterial activity and plant growth in addition to **being a** temporary source of essential plant nutrients such as phosphorus, nitrogen, potassium. calcium and magnesium. Organic material would also reduce drying during droughts because organic material has a high moisture retention capacity.

Unfortunately, many tailings impoundments in Canada are situated on the Precambrian Shield which is characterized in general by extremely low amounts of suitable cover **material. The overall scarcity** of large volumes of natural organic material might be offset by using other materials such municipal compost, provided that transportation costs to the mining industry were reasonable.

1.3 Municipal Compost as a Source of Organic-Rich Material

Composting is the biological decomposition of organic material under varying degrees of control which produces a relatively stable organic end product used as a soil enhancer.

It is estimated that up to 30% of non-hazardous municipal solid waste (MSW) is readily compostable and is therefore a potential source of organic material for reclamation. The compostable fraction is primarily organic waste, such as food and yard wastes, although paper products are compostable and are sometimes included in the compostable fraction. Large quantities of sewage sludge are also available for composting across Ontario.

The provincial government and municipalities are showing increasing interest in large scale composting. Scenarios proposed by the Municipality of Metropolitan Toronto in its master plan for solid waste management (to take effect in 1996) include gradual implementation of large scale composting options ranging from 500,000 to over 1.25 million tonnes of organic waste (250,000 to 600,000 tonnes of compost) per annum. Production of this magnitude exceeds current demand and new uses must be sought.

Assuming that 1 tonne of organic waste generates 0.5 tonnes of compost, then 1 million tonnes of organic waste would produce enough compost to cover 100 hectares to a depth of 1 m assuming a bulk density of 0.5 tonnes of compost per m’. This is a very small fraction of the extensive tailings area in need of reclamation in Canada and it is likely that compost derived from MSW could be applied to tailings for many years.

The advantages of using municipal waste to help solve the mining industry’s waste problem are compelling and should be looked upon favourably by the general public and regulatory bodies. Not only would there be improvements in the quality of tailings discharge but urban communities would reduce their dependence on landfill. Large scale cornposting could go a long way to meeting the provincial government’s target of diversion of 50% of municipal waste from landfill and incineration. The situation is timely for both the mining industry and municipalities to consider the mutually beneficial application of compost from MSW to rehabilitate tailings sites.

2. SOLID WASTE COMPOSITION AND DISTRIBUTION IN ONTARIO

2.1 MSW Composition

Effective waste management planning requires information on the amounts and types of solid wastes generated. Several waste composition studies have recently been conducted in Ontario - the Metro Toronto Solid Waste Composition Study and the Ontario Waste Composition Study. The results for the residential sector were similar but different methodologies for the ICI (industrial, commercial and institutional) sector preclude comparison of the ICI results from the two studies.

Metro Toronto Solid Waste Composition Study: The organic waste fraction (yard plus kitchen waste) in post-blue box residential waste was 31%. This may decrease somewhat as participation increases in the home composting program. The average organic waste fraction in the post-recycling ICI sector was 18%. The avenge post-blue box organic waste fraction of MSW currently going to landfill is 23% in Metro Toronto assuming a mix of 60% ICI and 40% residential. The average organic waste fraction will likely be slightly higher in Ontario communities with a smaller ICI sector.

Ontario Waste Composition Studv: Estimates of kitchen waste ranged from 26 to 29% in the residential sector of three Ontario communities (East York, Fergus and North Bay) in 1989-1990. Yard waste was not included. Food waste in the ICI sector in the Regional Municipality of Waterloo ranged from 0.55% in the retail furniture. appliance, floor covering and furnishings sector to 57% in the take-out food sector. An' average value for the ICI sector was not calculated.

Other Studies: Organic waste fractions in several American surveys ranged from 16 to 33% (summarized in Denison and Ruston 1990).

The fraction of organic waste in a small community obviously depends upon the proportions of residences and businesses as well as the type of dwellling and business. However, across larger regions it is assumed that these proportions will approach the average value for Ontario. Furthermore, it is reasonable to assume that not all organic waste will be captured.

The Metropolitan Toronto Solid Waste Management Master Plan (1991) combined several studies and assumed for planning purposes that the average organic waste fractions were 36% (residential) and 13% (ICI) for an average organic waste fraction of 22%.

The 'operationally obtainable' organic waste fraction is assumed **here to be 17% of the** total waste stream in Ontario. **This is the organic waste which will be collected if high participation rates occur across all sectors.** This percentage is derived by assuming a organic waste fraction of 24%, a participation rate of 90% and a capture efficiency of 80% across Ontario.

2.2. Distribution of Waste in Ontario

Data were collected for those municipal governments responsible for waste disposal. Under current legislation in Ontario, waste collection is the responsibility of area municipalities (cities) while waste disposal is the responsibility of the regional government in regional municipalities and area municipalities in counties and districts. MSW generation rates in Ontario were estimated from 1986 census data for regions and cities with populations greater than 40,000 (Table 1) representing over 80% of the population.

Smaller municipalities were ignored in this report. However, the trend in waste management is towards increasing coordination and planning, particularly among area municipalities in counties, which will undoubtedly increase the quantity of waste.

MSW generation rates were estimated by assuming an annual per capita generation rate of 1 tonne from the residential and ICI sectors from areas outside the Greater Toronto Area (GTA) and 1.1 tonnes within the GTA. The higher per capita rate in the GTA is attributed to higher industrial, commercial and institutional activity.

Landfill data obtained from municipal works departments are also presented in Table 1. Landfill data were not always in agreement with estimates derived from population data either because landfills were accepting waste from other municipalities or were exporting to other regions. Outside of the Greater Toronto Area, population derived estimates are considered in this report to be a more reliable estimate of MSW generation rates than measurements of landfill tonnages.

Table 2 presents operationally obtainable organic waste fractions for major urban areas in Ontario. These data were derived from MSW data in Table 1 assuming an operationally obtainable organic waste fraction of 17% of the total MSW stream. About 1.4 million tonnes of operationally -obtainable organic waste are generated each year in Ontario of which about 53% originates in the Greater Toronto Area and 29% originates in southwestern Ontario. Approximately 87,200 tonnes (6%) are generated each year in northern Ontario. Over 680,000 tonnes of compost could potentially be produced in Ontario annually, assuming a 50% reduction in weight during composting. All of Ontario’s annual compost production would cover 136 hectares per year to a depth of 1 m assuming a bulk density of 0.5 tonnes/m’. Given that approximately 15,000 hectares of tailings are in need of reclamation, unlimited composting application could occur for many decades.

Table 1. MSW generation rates derived from 1986 census data and 1990 MSW landfill data (tonnes per year unless specified) for major urban areas in Ontario. MSW generation rates were estimated from population data by assuming an average per capita generation rate of 1 tonne per year from residential, institutional, industrial and commercial sectors for non-GTA municipalities and 1.1 tonnes for GTA. Landfill data were obtained from municipal works departments and often include sewage sludge.

	Tonnes MSW/year	
	Population	Landfilled
Central		
Barrie	48,286	83.000
Peterborough	87.080	55.000
subtotal	135,400	138,000
South West		
Brantford	76,920	120,000
Cambridge	79,920	363,300
Chatham	42,210	4,360 m^3
Guelph	85,962	**
Haldimand-Norfolk Region	90,000	**
Hamilton-Wentworth Region	557,029	300,000
London	342,302	265.000
Niagara Region	370.000	**
Samia	85,700	32,650 m^3
Windsor	253,988	189,000
Waterloo Region	311,195	**
Woodstock	26385	504.600 m^3
Subtotal	2321,600	**
South East		
Belleville	40,000	163,000
Cornwall	46,425	45.830
Kingston	122,350	100.000
Ottawa-Carleton Region	606.639	250.000
Subtotal	815,400	558,800
North West		
Kenora	52,834	7,700 m^3
Thunder Bay	122,217	178.000
subtotal	175,000	185,700
North East		
North Bay	57,422	50,000
Sault Ste. Marie	84.617	70,700
Sudbury Region	148.877	25,000
Tiimins	46.657	m 100,000
subtotal	337,600	245,700

..... Table 1 continued.

Table 1. Continued.

	Tonnes MSW/year	
	Population	Landfilled
Greater Toronto[1]		
Durham Region	373,000	400,000
Halton Region	314,000	200,000
Metro Toronto Region	2,500,000	2,500,000
Peel Region	666,000	700,000
York Region	385,000	500,000
subtotal	4,238,000	4,300,000
TOTAL	8,023,000	

1. MSW data from MOE Backgrounder No. 2. November, 1990.

Table 2. Operationally obtainable organic waste (tonnes/year) generated by major urban areas in Ontario. The operationally obtainable fraction is assumed to be 17% of MSW. The final compost tonnage assumes a reduction of 50% in weight during composting. MSW generation rates are listed in Table 1.

	Organic Waste	Compost
Central		
Banie	8,200	4.100
Peterborough	14,800	7,400
subtotal	23,000	11500
South West		
Brantford	13,100	6,550
Cambridge	13,600	6,800
Chatham	7,200	3.600
Guelph	14.600	7,300
Haldimand-Norfolk Region	15,300	7,650
Hamilton-Wentworth Region	94,700	47350
London	58,200	29.100
Niagara Region	62,900	31,450
Samia	14,600	7300
Windsor	43200	21,600
Waterloo Region	52900	26,450
Woodstock	4.500	2,250
subtotal	394,700	197,350
South East		
Belleville	6,800	3,400
Cornwall	7.900	3,950
Kingston	20,800	10,400
Ottawa-Carleton Region	103.100	51.550
subtotal	138,600	69300
North West		
Kenora	9,000	4,500
Thunder Bay	20.800	10.400
subtotal	29,800	14,900
North East		
North Bay	9,800	4,900
Sault Ste. Marie	14,400	7,200
Sudbury Region	25,300	12,650
Timmins	7.900	3.950
subtotal	57,400	28,700

..... Table 2 continued.

Table 2. Continued.

	Organic Waste	Compost
Greater Toronto[1]		
Durham Region	63,400	31,700
Halton Region	53.400	26.700
Metro Toronto Region	425,000	212500
Peel Region	113,200	56,000
York Region	65,500	32,750
subtotal	720,500	360,250
TOTAL	1,364,000	682,000

1. Organic waste derived from measured landfill tonnage.

3. ORGANIC WASTE COLLECTION AND COMPOSTING METHODS

3.1 Collection

Organic waste can be separated 'at source' by the waste generator or it can be isolated from mixed waste at a centralized waste sorting facility. In general, compost quality is expected to be higher (less contamination with debris and chemical pollutants) when waste is separated at source into appropriate streams and carefully handled. For example, the recent Ontario Ministry of the Environment Downsview Resource Recovery Project in Toronto mechanically separated mixed residential waste into several streams and found an unacceptably high degree of physical contamination of compost with plastic and other inert material Coloured plastic debris is highly visible today in soils around the plant amended with compost. If similar compost were applied to flooded tailings, plastic debris would inevitably become free and litter areas downstream.

Several curbside mixed waste collection methods extract recyclable goods to varying degrees (see SWEAP Discussion Paper 3.2 for a more detailed review). Examples of curbside collection methods are (1) no separation, (2) the currently popular residential blue box + residual waste system, (3) the wet/dry system and (4) the three stream approach of dry recyclables, organic waste and residual waste.

Method 1 is the conventional method used by virtually all North American municipalities until recently. Waste was treated as unusable and landfilled or incinerated.

In the blue box method, recyclable dry goods such as cans, glass bottles, plastic containers and newspapers are placed in a separate container by the waste generator (i.e. separation at source) leaving organic waste and unusable waste mixed together in another fraction.

In the wet/dry method, waste generators separate waste into two fractions both of which contain recyclables and non-recyclables - a 'clean and dry' fraction and a 'wet and dirty' fraction. The 'wet and dirty' fraction contains the compostable fraction. The wet/dry method produces two low quality waste streams because of the presence of undesirable wastes and is inconsistent with the notion that efficient separation is necessary to produce high quality material to meet market requirements. Consequently this method may limit diversion rates from landfill.

Additional sorting of the 'wet and dirty' stream via a mechanized central sorting facility prior to composting or post-production cleaning of the compost. may produce an acceptable final product. This cost can be avoided by the municipality if the burden of separation is placed on the waste generator (i.e. the three stream method) although collection logistics may be somewhat more complicated,

The three stream approach will produce the highest quality materials and therefore will likely divert more waste than the two stream approach particularly when markets are soft and markets for low grade commodities shrink. The three stream collection method was recommended for implementation by 1994 in Metro Toronto (Metropolitan Toronto Solid Waste Management Master Plan, 1991; Plan synopsis is included in Appendix A this report).

The provincial government in Ontario will require source separation by all sectors once enabling legislation has been passed (see Section 5.1). Therefore, it is expected that all municipalities and businesses in Ontario will use the three stream collection method.

The residual waste stream may be compostable although it will undoubtedly produce a very low quality product with a high percentage of inert material and possibly some contamination with metals and organic chemicals. Physical processing of the compost to remove inert material would likely be required before shipment.

3.2 Composting

Composting is the biological, primarily microbial, decomposition of organic material under varying degrees of control which produces a relatively stable organic end product used as a soil enhancer (Diaz et al. 1982). Technology is used to optimize critical environmental variables such as oxygen, particle size, moisture and temperature and promote microbial growth rates. The technologies briefly described below pertain directly to centralized facilities rather than backyard composting. Composting is described in more detail in the Provincial Compost Guidelines (attached as Appendix B).

Composting technology is divided into hvo general types, windrow (open) and mechanized (closed or in-vessel) (Diaz et al. 1982). The windrow is a low technology method in which piles of waste arc left exposed. Aeration is accomplished by periodic turning .with heavy equipment or by forced aeration. Turning also promotes decomposition of surface material by moving it inside the windrow. As the length of exposure depends on climatic conditions, long periods of time are required for decomposition to reach a suitable state, particularly during Canadian winters. Open systems may produce objectionable odours and attract bids and other scavengers.

In mechanized systems, closed reactors are used to exert more control over environmental variables and accelerate the first stages of decomposition. In a typical plug flow system waste moves through a composting vessel and exits after a residence time of approximately 3 days. The compost requires further decomposition and is stacked in windrows allowing it to mature for approximately 6 weeks. Although the residence time in-vessel is short, it greatly speeds up the decomposition of labile organic material, hence, subsequent outdoor maturing is not objectionable.

4. GOVERNMENT COMPOSTING POLICY IN ONTARIO

4.1 Provincial Policy

The general intent of the provincial government is to spawn greatly increased 3R's activity with composting playing an important role. The provincial government released 'Regulatory Measures to Achieve Ontario's Waste Reduction Targets' in October of 1991 and has tabled enabling legislation with amendments to the Environmental Assessment Act, Environmental Protection Act and Municipal Act. The government intends to make waste audits and workplans, source separation in the ICI and municipal sectors and cornposting of leaf and yard waste mandatory. Collection and cmposting of kitchen waste is expected to follow.

There is some concern that compost derived from municipal waste may be contaminated and that uncontrolled use of contaminated compost poses an environmental risk. In response to these concerns. the Ontario Ministry of the Environment issued 'Guideline for the Production and Use of Aerobic Compost in Ontario' in 1991 (Appendix B this report). The Guideline outlines required approvals and permits, facility siting criteria, operating conditions and compost quality specifications.

Compost meeting all of the guidelines and criteria would be permitted unrestricted use. Compost not meeting guidelines will be considered a processed organic waste under Regulation 309 and "In this case, the MOE will require Waste Disposal Site approvals for locations where compost is applied, and Waste Management Systems approval for handling it." Although the provincial government does not have a policy specifically governing application of contaminated compost to mine tailings at this time, land reclamation projects are suggested as potential sites for low quality compost ('Guideline for the Production and Use of Aerobic Compost in Ontario*, page 8, Section 7.1).

The derivation of compost quality specifications (pages 8 - 11 of the 'Guidelines for the Production and Use of Aerobic Compost in Ontario') is explained in Appendix 1 of the Guidelines on pages 14 and 15). Metals criteria were derived from Ontario guidelines for rural soils ("Upper Limit of Normal" Contaminant Guidelines for Phytotoxicity Samples, MOE) and total salts and sodium absorption ratio limits were taken from *Guidelines for the Decommissioning and Cleanup of Sites in Ontario' (MOE 1990). Compost particle size was based on past

MOE experience (presumably the Fairfield Digester **at Downsview). Composting** literature **was** reviewed, **including** Florida Department of Environmental Regulation, Rule **17-709,** "Criteria for the Production and Use of Compost Made from Solid Waste". but there is no indication of the importance of given documents to criteria development other than those cited above.

43 Metro Toronto Policy

Metro Toronto appears committed to both large-scale and back yard composting activity. Back yard cornposting does **not** require formal approval and reduces the need for large investments in time and money for land acquisition and equipment. However, backyard composting will not divert a majority of organic wastes because it cannot serve the ICI sector and apartment dwellings. To illustrate, if we assume 90% participation of single family dwellings in backyard composting in a community in which 50% of the residences are apartments and 50% of the organic waste is generated by the ICI sector, then backyard composting will divert approximately 15-20% of the total operationally obtainable organic waste stream. Hence, large scale cornposting is necessary.

Metro Toronto recommended that a prototype facility be built before 1995 capable of composting up to **500** tonnes/day of source separated organic waste (Metropolitan Toronto Solid Waste Management Master Plan, 1991; see Appendix A this report), which is **about 25%** of Metro Toronto's operationally obtainable organic waste. and has inititiated a site selection process for **centralized composting** facilities. The prototype facility is 'intended to demonstrate the feasibility of large scale composting. provide a basis for determining the characteristics of the finished product and establish marketability' (page 8.5 of the Master Plan). The plant would produce about **75,000** tonnes of compost annually.

Two to three more facilities of comparable size are expected by the year 2000 (page 8.6 of the Master Plan) each costing approximately $35 million exclusive of land costs. Hence, within 9 years Metro Toronto is expected to separate up to 410,000 tonnes of organic waste and produce approximately 300,000 tonnes of compost. In comparison, this report estimates that Metro Toronto can separate 425,000 tonnes of organic waste and produce 212,000 tonnes of compost (Table 2). Apparently, the Master Plan **assumes** a much smaller weight loss during composting, only **27%,** compared to the assumption in this report of 50%. An official for Metro Toronto Works Department suggested that the weight loss would be 40%. The actual loss will depend upon feedstock composition • for example, yard waste may differ greatly from kitchen waste.

Metro Toronto initiated a composting pilot project in late 1991 involving 13,000 homes in Etobicoke. North York and Toronto. Source separated organic waste is collected and delivered to the recently retrofitted 50 tonne per day Fairfield Digester located at the Dufferin Transfer Station in North York,

The composting policies of other municipalities have not been reviewed but are likely to be similar to Metro Toronto policies given the provincial objective of implementing 3R's programs uniformly around the province. Guelph is currently operating a pilot project comparing compost from two stream and three stream collection methods.

5. COMPOST QUALITY AND MARKETABILITY

Municipalities will seek to produce high quality compost that meets Ontario Ministry of the Environment specifications for unrestricted use in spite of the cost because it will expand their opportunities for diversion from landfill. The most desirable markets for municipal compost will be those nearest to cornposting facilities because proximity of market reduces transportation costs. In southern Ontario, the most promising markets are horticulture and agriculture. Furthermore. compost meeting Ministry specifications could be shipped to anywhere in the province without fear of adverse public reaction because the waste will have been transformed into a high quality commodity and will no longer be considered waste.

However, some compost may not meet MOE specifications for unrestricted use in spite of proficient collection and composting methods. Knowing the proportion of compost not meeting MOE specifications will be important because the cost of disposing of rejected batches could be a significant operating cost. However, few data relating organic waste source, collection method and compost quality exist. It is generally assumed that yard and kitchen wastes will produce uncontaminated compost provided they are properly separated at source. Flindall and Haight (1991) compared some compost quality data for household separated waste in the Netherlands and mechanically separated mixed waste in Toronto. Concentrations of metals (cadmium, chromium, copper, lead and zinc) in the Netherlands study were below the draft Ontario guidelines for unrestricted use (Ontario Ministry of the Environment, 1991a) while concentrations of eight of 11 metals in the Toronto study exceeded the guidelines.

In practice, compost batches utilizing source separated organic waste will occasionally be contaminated with inert debris and high priority organic and inorganic chemical contaminants. The level and frequency of contamination will probably be a function of the proportion of non-kitchen and non-yard wastes finding their way to the composting facility.

Additional &ta is expected to be forthcoming from the current Guelph pilot project. The objectives of the Guelph project are to compare organic waste capture efficiencies and compost qualities using the two stream and three stream collection methods. Compost products from both collection methods are similar and may meet MOE guidelines (City of Guelph Wet/Dry Pilot Project Summary of Preliminary Findings, 1991); however, the amount of waste collected is small enough to permit efficient hand sorting and this may account for the similar qualities (Mike Gibson, City of Guelph, personal communication).

If municipalities throughout Ontario are to be persuaded to engage in large scale composting activity to meet provincial diversion targets they must be assured that there will be markets for all compost produced In northern Ontario, horticulture and agriculture markets are small and may be too small even for the limited amounts of compost northern Ontario could produce. There must also be a ready market for contaminated compost so it need not end up in landfill. Tailings reclamation is proposed here as a suitable alternative/addition to agricultural and horticultural markets.

The use of contaniinated compost bears consideration by the province and the mining industry. If compost metal levels are quite low relative to tailings, use of contaminated compost could be acceptable where overall environmental improvements can be shown to occur. However, in examining this issue, the presence of organic contaminants may be a cause for concern and should be adressed in additon to metals. Conditions could be defined under which rejected batches are deemed acceptable as tailings cover.

6. COMPOSTING SEWAGE SLUDGE

Municipal wastewater treatment plants produce a sludge byproduct during treatment of sewage. Sludge is a material of high organic content which is readily compostable but which, unfortunately, is frequently contaminated with a large number of high priority organic and inorganic contaminants. Sludge disposal is a problem for municipalities partly because of contamination. Conversations with several municipal works departments revealed a range of sludge disposal options including landfill, incineration, and spreading on agricultural lands.

Sludge is often thickened, stabilized and dewatered before disposal. Thickening and dewatering serves to increase solids content from about 2% to about 25%. Stabilization serves to reduce pathogens, volatile organic solids (and therefore odour), volume and weight. Common stabilization methods include anaerobic and aerobic digestion, composting and lime addition (Water Pollution Control Federation 1985). Raw or digested sludge are compostable. A solids content of 50% is considered optimum for composting, hence, bulking agents are usually added to improve aeration.

Composted sludge appears to be a more desirable end-product than other forms of digested sludge because it is less objectionable and cheaper to transport; however, composting is more expensive than other stabilization methods (Water Pollution Control Federation 1985).

No reports were located on composted sludge application to artificial wetlands on tailings. However, Seaker and Sopper (1988a, 1988b) reported the results of applying a mixture of composted and anaerobically digested, dewatered sludge to terrestrial minespoils. They concluded that 'sludge amendments enhance soil formation and site stabilization in minespoil at a more rapid rate than does chemical fertilizer.' Growth of tall fescue improved on acid mine soils when soils were amended with a mixture. of composted garbage and sewage sludge (Stout et al. 1982). Beneficial uses of municipal sludge is briefly reviewed in 'Water Pollution Control Federation, Manual of Practice FD-15 (1989)'.

Metro Toronto's Main Treatment Plant at Ashbridges Bay serves about 1.25 million people and produces an average of 120 to 130 tonnes per day of dewatered, anaerobically digested sludge which is incinented. The plant could produce 10.000 tons of compost per year assuming an average solids content of 25%. It appears reasonable, therefore, to assume that at least 30,000 tonnes of composted sludge could be produced in Ontario.

The Ontario Ministry of the Environment requires that sewage sludge be stabilized by aerobic digestion or other approved methods before being spread on land. Application is restricted near surface and ground waters and sludge cannot be applied to soils with pH less than 6 because nitrification (the bacterial production of nitrate from ammonium) can lower soil pH. State and provincial regulatory requirements are summarized in Water Pollution Control Federation, Manual of Practice FD-15 (1989).

Sludge from sewage treatment plants in Ontario is typically contaminated with a suite of metals and high priority organic contaminants (Ontario Ministry of the Environment 1988). Although metal levels may be very low relative to levels present in tailings, organic contaminants may be cause for concern. Government and the mining industry should review whether composted sludge application to tailings is environmentally desirable. Provincial approval for application of digested or composted sludge to flooded tailings will probably be necessary.

7. COST ANALYSIS

7.1 Composting

The cost of cornposting is related to.the composting method and likely the scale of the operation. Commercially available composting methods have been reviewed by Diaz and Savage (1982). Composting sludge is also considerably more expensive than cornposting organic waste according to a review by BioCycle (1991).

In the United States, estimated operating costs ranged from US$9 per ton for a 300 ton/day solid waste windrow operation to US$85 per ton for a 90 ton/day windrow opention (BioCycle 1991. page 45) (CAN$10 • $89 per tonne). Of the 15 facilitites for which cost data were cited, operating costs for 11 ranged from CAN$26 to $52 per tonne. (Although not stated, the costs are probably expressed per ton of compost rather than per ton of organic waste.) Most sludge composting costs in the U.S. ranged between US$125 and $175 per dry ton (CANS131 • $183 per dry tonne).

The estimated capital cost for each Metro Toronto composting facility with an annual production capacity of 75,000 tonnes of compost is $35 million exclusive of land costs. For comparison purposes I have made the simplistic assumption that Metro Toronto will debt finance the entire capital cost at 10% over a ten year period. On this basis, the annual capital payment is $74 per tonne. Assuming the operating costs will be $26 to $52 per tonne, the total annual cost will be $100 • $126 per tonne in constant dollars.

7.2 Transportation

Transportation of compost in bulk is the preferred method in terms of logistics and cost. Bagging imposes extra costs on both ends (bagging and emptying) and typically produces an unecessary waste problem • disposal of bags.

Due to its relatively high moisture content, compost will freeze during winter shipment. Hence, bulk transportation would most likely be seasonal. Compost would have to be stored at or near composting facilities during the winter months.

Since transportation costs and method depend upon origin, destination and quantity, a general cost analysis was not prepared for all of Ontario. I chose instead to examine one possible scenario - shipping 150,000 tonnes of compost each year from the Greater Toronto Area to Elliot Lake via rail, truck or water. The cost estimates provided are probably on the high end. since they were obtained without the benefit of serious negotiations.

CP Rail: The probable location of the composting facilities and tailing sites are relatively close to CP lines. An approximate estimate was provided by Earl Komack, a marketing representative with CP Rail Special Projects in Toronto (telephone: (416) 863 8313). The estimate was based on the assumption that open gondola cars with a cubic capacity of 1746 cubic feet (50 m^3) would be filled to their maximum capacity of 98 tons (89 tonnes) for an assumed density of 1.8 tonnes/m’. Gondola capacity can be increased on dedicated cars by welding walls onto the cars.

Cost:

1. Loading gondola cars in west Toronto - \$2 per tonne.
2. Rail transfer from west Toronto to Spragge - \$20 per tonne.
3. Unloading, transfer and trucking from Spmgge to Elliot Lake - \$8 per tonne.

Adding \$5 per tonne to load and truck compost to CP Rail’s west Toronto yard yields a total cost of approximately \$35 per tonne plus GST based on a density of 1.8 tonnes/m’. The cost of rail transfer from west Toronto to Spragge using a more realistic density of 1.1 tonnes/m’ is \$30 per tonne with a total cost of \$45 plus GST.

Compost density is an important factor in transportation cost but it is difficult to estimate. Bulk density for spent mushroom compost has been reported at 0.65 tonnes/m^3 although density during transportation might be increased with an appropriate loading technique. Truck and rail loading techniques should be reviewed for their effect on density.

Trucking: An estimate of \$42.35 per tonne for trucking 150,000 tonnes from Toronto to Elliot Lake based on a density of 0.5 tonnes/m^3 was provided by LCI Environmental Inc. (contact John Fowler, telephone: (416) 615

0935). Loading and unloading charges would bring the total cost to approximately $46 plus GST. about the same as rail transport.

Trucking may be the only alternative when composting facilities and tailing sites are not near rail lines or for short hauls.

Water. Shipment by water may be a cost-effective alternative when tailing sites and composting facilities are located near Great Lakes ports. ULS (contact Wayne Hennessy, telephone: (416) 920 7610) provided an estimate of $6.00 - $6.25 per tonne for shipping 150,000 tonnes from Hamilton to Elliot Lake based on a density of 0.5 tonnes/m'. This estimate includes all charges against the vessel (but not the cargo), lockage and harbour charges but excludes trucking, Seaway charges against the cargo, wharfage and stevedoring. It assumes that the ship is a full sized lakes self unloader (40.000 m^3 or 20,000 tonne capacity) and a 'fast as can' cargo discharge (unloading) rate of 5 to 8 hours. Eight monthly consignments of 20,000 tonnes each are required. As bulk cargoes are not readily handled at the Toronto Harbour facilities, I was directed to Seaway Terminals in Hamilton, a private wharf owner/operator (contact Ken Gange, telephone: (416) 528 8741). Loading is expected to take 4 to 5 days. The Spragge wharfage and stevedoring costs were provided by Reiss Lime Ltd. in Blind River which owns the harbour facility (contact Al Lucas, (705) 849 2201).

Total charges:

1. Loading and trucking to Hamilton Harbour $5/tonne,
2. Shipping from Hamilton Harbour to Spragge 86.00 to 6.25/tonne,
3. Welland Canal cargo toll of $0.52/tonne,
4. Wharfage fee in Hamilton: no charge for storage of 20,000 tonnes for 30 days, $0.50 per tonne thereafter,
5. Scale-in and loading at Seaways Terminal in Hamilton Harbour $2.50/tonne,
6. Stevedoring cost in Hamilton of $7.50/tonne,
7. Hamilton Harbour cargo charge of $0.4405/tonne,
8. Stevedoring (throughput) cost in Spragge of $2.50 per tonne,
9. Trucking from Spragge to Elliot Lake $5/tonne.

The estimated total shipping charge is $30 per tonne plus plus GST which is significantly less than rail or trucking.

How many trucks are required at each end? Approximately 670 truckloads with a capacity of 30 tonnes per truck are needed to move 20,000 tonnes each month or an average of 30 truckloads per 7.5 hour work day. If a round trip between wharf to facility takes 2 hours, then a minimum of 8 dedicated trucks will be required at each end. If it takes 15 minutes to load 30 tonnes into a truck, then 30 trucks can be loaded each day assuming a 7.5 hour day and one set of loading equipment.

The above analysis was intended to serve only as a guide. The choice of transportation method will depend in the end upon the locations of producers and end users and quantity.

7.3 Solid Waste Management Policy Implications

The cost of landfilling is probably less than $50 per tonne in most municipalities whereas estimated composting costs are $100-5126. In Metro Toronto private haulers pay a landfill tipping fee of approximately $150 per tonne while area municipalities pay much less. In effect, residential waste disposal is significantly subsidized by the private sector. Although private sector tipping fees will subsidize centralized composting to some degree, there appears to be little or no financial incentive for municipalities to divert waste from landfill and engage in centralized composting without provincial incentives or ‘encouragement* to meet diversion targets.

We can expect that municipally owned cornposting facilities, even if they do not pay the full tipping fee, will choose to ship excess or contaminated compost to a tailings site rather than landfill it because of these same incentives. The incentive for privately owned cornposting facilities will be financial • it is cost-effective to ship compost to a potential tailings site and avoid high landfilling fees. These arguments are predicated upon the assumption that the mining industry will not pay for compost but will be a willing recipient.

8. **TAILINGS** RECLAMATION PROGRAMS AND METHODS

8.1 Reclamation Programs

The seriousness and extent of AMD in Canada has prompted the mining industry and the federal and several provincial governments to cooperate in investigations of innovative methods for long-term, environmentally effective management of tailings that would allow mine operators to walk away from a site after closure with minimum subsequent long-term active management. According to the federal government, "Over 15,000 hectares of acid-generating mine wastes have been identified at operating mine sites in Canada. Site rehabilitation would cost more than $3 billion during the next 15 years, a cost unacceptably high to the mining industry if it is to remain competitive. Some [abandoned] sites are the responsibility of the Crown and solutions to AMD are, therefore, of significant interest to the public through provincial and federal governments" (CANMET fact sheet). In Ontario, 2000 abandoned mine sites have been identified and at least 20 sites covering 830 hectares pose an AMD problem (Feasby et al. 1991). Responsibility for reclamation of abandoned tailings rests with the Ontario Ministry of Northern Development and Mines.

In response, the Canada Centre for Mineral and Energy Technology (CANMET) of Energy, Mines and Resources Canada, initiated the Mine Environment Neutral Drainage (MEND) program with representation from federal, provincial and industrial interests. "MEND is a co-operative research organization sponsored, financed and administered by the Canadian mining industry, the Federal government and the provinces of British Columbia, Manitoba, Ontario, Quebec and New Brunswick" (MEND Annual Report. 1991).

Some 34 MEND sponsored research programs have been initiated since 1988 with a budget of $4.8 million and 21 projects were completed by the end of 1990. Research and development have been undertaken in 5 main areas: AMD prediction, prevention and control, treatment, monitoring and technology transfer. Prevention and control has received the largest budget. "Some of the most promising results have been obtained during the studies into the prevention and control of acidic drainage using barriers and solid covers" (MEND Annual Report, 1991).

Choice of reclamation method is site-specific, for example, flooding may not be appropriate at all sites.

Nevertheless, revegetation should be a goat in all reclamation projects for reasons of aesthetics and erosion control.

After a series of studies and a review of reclamation approaches, Rio Algom Limited has recommended the wet tailings approach for the decommissioning and reclamation of its Quirke Mine tailings (Balins et al. 1991). The objective is to raise the water table, maintain ponded water and promote vegetative growth. Flooding of one of the five engineered cells at the Quirke site, Cell 14 with a ponded surface area of 64 hectares, began in the fall of 1991 and should be completed by the summer of 1992. The remaining cells should be flooded by 1993 for a total ponded surface area of 192 hectares. The common cattail, Typha latifolia, will be planted in the shallow flooded areas (Al Vivyurka, personal communication). The cattail is a good candidate to initiate colonization because it is present in local wetlands, it is tolerant of metal-laden, very acid conditions (Kalin and van Everdingen 1987) and because it reproduces vegetatively via rhizomes (horizontal underground stems which produce emergent plants at intervals).

Rio Algom has also initiated a small field study of the effects of cover on AMD generation (Al Vivyurka, personal communication). The study design utilizes twelve 8 m by 11 m plots (six treatments in duplicate: no flooding. shallow flooded, deep flooded, compost cover, organic cover with cattails, cattails without cover). The water table in the non-flooded plots will be maintained about 1 m below the surface; all other plots will be flooded.

Falconbridge has recently completed a small field study of the effects of organic matter application on AMD production rates in irrigated test plots and is about to embark on further studies involving litenture reviews and lab and field testing under the auspices of the MEND program (Mark Wiieman, Falconbridge. personal communication).

Development of policy and planning and successful implementation of tailings reclamation projects with municipal compost will require the cooperation of many interested parties in Canada. For example, the federal government through Energy, Mines and Resources is a co-sponsor of MEND research program. Environment Canada would also be an interested party. Provincial governments are responsible for setting and administering environmental policy. In Ontario, several Branches of the Ministry of the Environment are involved (Water Resources Branch, Waste Management Branch and Waste Reduction Office set policy while Approvals Branch and regions administer policy). The Ontario Ministry of Northern Development and Mines (MNDM) is involved in tailing operations and rehabilitation and both Ministries participate in the MEND program. Municipal governments are charged with responsibility for developing municipal solid waste master plans and for soild waste diversion and disposal under the direction of provincial governments. The mining industry, of course, is responsible for managing tailings at operating sites (government is responsible for abandoned sites, specifically MNDM in Ontario) and the solid waste management industry may be asked to provide composting technology and services.

Over 400 wetlands have been constructed on mined lands in the bituminous coal region of the eastern U.S. for acid water treatment in climates which are considerably warmer than northern Ontario (Kleinmann et al. 1991). The U.S. Bureau of Mines is conducting a long-term evaluative study of many of these sites (Kleinmann and Girts 1987). Preliminary results from 20 wetlands surveyed by 1987 indicate that wetlands dominated by emergent plant species out-performed Sphagnum-dominated (moss) wetlands and that much of the water treatment was accomplished by diverse communities - bacteria, algae and plants - and by amendments such as mulch. The authors noted that survival of cattails was high in mine water with a pH of 3 or greater, with little replanting necessary and considerable spreading during the second growing season. The effectiveness of the constructed wetlands in meeting regulatory compliance was not evaluated.

The Tennessee Valley Authority (TVA) is in the process of planning and/or operating fifteen constructed wetlands for treating coal-related AMD. "TVA's experience suggests that constructed wetlands alone may be appropriate and very effective for treating weak to moderately polluted acid drainage on a long-term basis" (Brodie 1990). The wetlands are designed to promote biological diversity and appear to be fertilized with phosphorus and potassium in the first year of operation. The studies apparently did not include unfertiliied controls to examine the effectiveness of fertilizer applications in attenuating AMD.

The U.S. wetlands have been constructed primarily to treat acidic effluent rather than prevent AMD formation because the AMD originates from undergound seepages, hence, the studies have focussed on attenuation processes (reduction of metal concentrations and neutralization of acidity). The design of Rio Algom's Quirke tailings reclamation project differs somewhat in **that** their wetland system **is built** entirely on tailings in or&r to **minimize** AMD formation.

In general, retention of metals other than iron was very site specific and was apparently a function of biological structure (Dollhopf et al. 1988: Dave and Lim 1989; von Michaels 1987) and hydrology (Knight 1987; Dierberg et al. 1987).

8.2 Wetland Reclamation Methods

Ecologically, differences between flooded tailings and engineered sites will depend on the degree of moisture saturation maintained. This report assumes that both methods maintain a high degree of saturation and therefore discussion of wetland ecology is pertinent to both.

The central hypothesis proposed here is that the rate of AMD formation in flooded tailings or from sites with engineered covers will be lower and the rate of AMD attenuation will be higher in a biologically productive system with stable, mature, diverse wetland flora and substantial organic sediments than in an unproductive system with sparse flora and no organic sediment. The rationale for this is (i) heterotrophic microbial oxygen consumption in aquatic sediments is a function of annual wetland productivity, hence, increased productivity which **is a** function of diversity will ensure an effective oxygen barrier in organic **sediments** above the tailiigs, (ii) a stable, mature, diverse floral community is supported nutritionally and physically by sediments and the floral community in turn maintains a constant input of new organic detrital material to the bottom sediments with each annual **growth/dieback** cycle, (iii) AMD attenuation is a function of many biological processes (Dave and Lim **1989; von** Michaels 1987) which implies that biological productivity and diversity should be promoted, (iv) biological cover reduces transport of suspended tailings material downstream and (v) organic substrate has a relatively high ability to retain moisture which helps wetland communities withstand drought conditions.

One example of a desirable biological process is sulfate reduction by bacteria which proceeds under highly anoxic and organic carbon-rich conditions. Reduction of sulfate to sulfide results in the formation of certain insoluble metal sulfides, particularly iron sulfide. and production of alkalinity (Stumm and Morgan 1981; Rudd et al. 1986;

McIntyre et al. 1990). Hence, bacterial sulfate reduction is the antithesis of the oxidation of sulfide minerals which produces sulfuric acid in tailngs.

Oxidation of sulfide minerals could take place even under continuously saturated conditions if the rate of water movement through tailings is sufficient to supply oxygen (Kalin and van Everdingen 1987). It is possible, therefore, that AMD formation may occur at some locations in the Quirke Mine tailings although the overall rate is expected to be very low. Elevated metal levels would then be expected in these locations. The rate of AMD formation is probably related to the hydraulic residence time (Knight 1987; Dierberg et al. 1987: Dillon and Rigler 1974; Dillon and Molot 1990).

The oxidized zone (zone with oxygen present) in the bottom sediments of natural lakes, ponds and wetlands typically does not extend more than 2-4 cm below the sediment/water interface. In very productive (eutrophic) systems, surficial sediments are anoxic even when the overlying water column is oxygenated although a high annual nutrient loading rate is required to maintain a eutrophic state.

Undisturbed sediments exhibit a vertical redox potential gradient. The gradient is associated with a vertical sequence of microbially-mediated redox reactions beginning with reduction of O_2 (e.g., aerobic decomposition of oragnic matter) at the sediment surface when O_2 is present and followed in descending order by denitrification, nitrate reduction, fermentation, sulfate reduction, methane fermentation, and hydrogen gas formation (Stumm and Morgan 1981). Denitrification and sulfate reduction have ken shown to have important alkalinity producing reactions in atmospherically acidified systems (Rudd et al. 1986). Maintenance of vertical redox gradients in sediments, i.e. maintaining undisturbed sediments, will be vital to maintaining the effectiveness of artificial wetlands. Emergent vegetation are essential to maintenance of undisturbed sediments in large, shaliow ponds because they reduce wind shear at the water surface.

It is hypothesized that a single addition of compost is sufficient to 'jump-start' an artifical wetland and accelerate the formation of a mature floral community. Nutrient loading from natural sources such as direct atmospheric deposition, weathering, etc. should then be sufficient to nurture and maintain a productive community. The compost application rate should be such that reducing conditions capable of supporting sulfate reduction are well within the organic layer.

Although the nutrient content of compost is insufficient to be technically classified as a fertilizer, several studies have shown that compost promotes plant growth, presumably because of its nutrient content and physical properties. The application of a mixture of composted and anaerobically digested, dewatered sludge to terrestrial minespoils resulted in enhanced soil formation and site stabilization compared to application of chemical fertilizer (Seaker and Sopper 1988a, 1988b). Growth of tall fescue improved on acid mine soils when soils were amended with a mixture of composted garbage and sewage sludge (Stout et al. 1982).

The mean total phosphorus concentration of compost from the Guelph pilot project was 0.32% and the nitrogen/phosphorus ratio was 4.8. For comparison, typical surficial sediment phosphorus concentrations in unproductive Ontario Lakes ranged from 0.05 to 0.3% with nitrogen/phosphorus ratios of 8 (Dillon et al. 1990). Although phosphorus levels are probably sufficient to support plant growth, nitrate amendments might increase productivity and raise the pH. (Biological consumption of ammonium produces acidity, hence, ammonium should never be added to acidic systems.) The wetlands could also be amended with other nutrients, minerals and finely ground calcite upon construction.

Wetlands used for AMD treatment and prevention may result in exposure to and accumulation of high levels of metals by wetland flora and fauna with potentially toxic results (Dollhopf et al. 1988). Body burden analyses and bioassays (e.g. rainbow trout toxicity tests) should be an essential element of monitoring programs.

9. CONCLUSIONS

1. Construction of artificial wetlands is, in general, a viable technique for AMD prevention and attenuation. The technique has been successfully applied in the U.S. to treat acidic effluent rather than prevent AMD formation. Retention of metals other than iron is very site specific and is apparently a function of biological structure. The effectiveness of engineered covers is unproven.

2. The effectiveness of artificial wetlands or engineered covers is enhanced when organic material is added. However, sufficient quantities are in short supply near many tailing sites. Composted municipal organic waste may be a suitable source of organic material for tailings reclamation projects.

3. Solid waste management policies are rapidly developing in Ontario to the point where large scale composting is being seriously considered by provincial and municipal governments in order to meet provincial waste diversion targets. If municipalities throughout Ontario are to be persuaded to engage in large scale composting activity to meet provincial targets they must be assured that non-landfill uses are available. Tailings reclamation is proposed as a suitable alternative/addition to agricultural and horticultural markets. Furthermore, tailings reclamation may be an acceptable non-landfill use for contaminated compost.

4. The 'opemtionally obtainable' organic waste fraction is assumed to be 17% of the total waste stream in Ontario. This percentage is derived by assuming an organic waste fraction of 24%, a participation rate of 90% and a capture efficiency of 80% across all sectors in Ontario. The 'operationally obtainable' organic' waste fraction could produce approximately 680,000 tonnes per year of compost assuming a 50% weight loss during cornposting. All of Ontario's annual compost production would cover 136 hectares to a depth of 1 m assuming a bulk density of 0.5 tonnes/m'. Given that approximately 15,000 hectares of tailings are in need of reclamation, unlimited composting application could occur for many decades. About 30,000 tonnes of composted sewage sludge could also be produced annually.

5. The three stream waste collection method will most likely be implemented in Ontario. The method should minimize contamination levels and produce compost which meets the Ministry of the Environment's

guidelines for unrestricted use. Nevertheless, some compost batches will likely not meet the guidelines for unrestricted use.

6. The legal and environmental ramifications of contaminated compost application to tailings must be addressed.

7. The rate of compost application to flooded tailings should be such that reducing conditions capable of supporting sulfate reduction are well within the organic layer. This operational criterion is best translated into tonnes/m^2 empirically.

10. RECOMMENDATIONS

1. Coordination of composting and tailings reclamation policies is essential for success. A policy planning group should be formed consisting of representatives from the mining industry, composting industry, municipalities (perhaps from an umbrella organization of municipalities), the Ontario Miitry of the Environment (Water Resources Branch, Waste Management Branch, Waste Reduction Office and possibly Northeast and Northwest Region offices), the Ontario Ministry of Northern Development and Mines, Environment Canada and Energy, Mines, Resources Canada (CANMET).

2. Criteria should be developed governing conditions under which contaminated compost is deemed acceptable as tailings cover. Liability concerns should also be addressed.

3. Test plots and pilot field projects are urgently needed to evaluate the effectiveness of compost application using permanently flooded amended (treatment) and unamended (reference) ponds. 'The pilot projects should monitor long-term changes in water quality (pH, Gran alkalinity, metals, nutrients, oxygen, temperature, conductivity, dissolved organic carbon, sulfate, major cations, etc.), sediment chemistry. sediment oxygen consumption rates, biological productivity and community structure, metal bioaccumulation in selected species, toxicity of standing waters (e.g. rainbow trout bioassays), and acid neutralization and metal attenuation rates and processes. Field studies should consider pond design features which promote biological diversity. The collaboration of aquatic ecologists. microbiologists, hydrogeochemists and biogeochemists will be necessary.

Questions to be addressed:

a. minimum/optimum compost application rates.
b. metal bioaccumulation in food chain, e.g. fish, waterfowl, macrophytes, and toxicity of standing waters.
c. pond design features for optimal AMD attenuation/prevention: e.g. optimum water residence times, shoreline complexity and varying depth to promote biological diversity.
d. relationship of biological diversity to AMD attenuation/prevention.
e. relative importance of various neutralization/metal attenuation processes.
f. seasonal effectiveness of wetlands.

4. Organic wastes should be solicited for pilot projects and test plots. Composted food processing wastes and sewage sludge should be considered as potential sources due .to the present lack of sizable source-separated municipal collection programs. Compost derived from mixed municipal waste is not recommended.

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