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The Effect of C:N Ratio on Bench-Scale

Composting of Pulp & Paper Biosolids

by

Kevin Lee Larsen

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THE EFFECT OF C:N RATION ON BENCH-SCALE
COMPOSTING OF PULP & PAPER BIOSOLIDS

BY

KEVIN L. LARSEN

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

of
MASTER OF SCIENCE

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ABSTRACT

In Canada and worldwide, increased biosolids production, new environmental legislation, and closure of landfill sites increasingly affect the pulp and paper industry. The total amount of biosolids requiring management has increased over the past several decades thereby gradually increasing interest in the quality of biosolids and the potential for beneficial use. Traditional methods of sludge disposal by landfilling are being replaced by new disposal methods, methods that take advantage of at least one of the nutrient, soil conditioning, or fuel properties of sludge. These utilization alternatives reduce the volume of material that is landfilled and recovers valuable materials such as nutrients and/or energy.

Each year, the pulp and paper mills in Canada landfill 1.4 million tonnes of waste material that would be suitable feedstock material for composting operations. This figure represents 64% of the total compostable material landfilled by the Industrial, Commercial, and Institutional sector in Canada. In 1995, only 4% of the mills' compostable material were diverted from landfills to composting.

The Pine Falls Paper Company (PFPC) Ltd., located in Pine Falls, Manitoba, Canada, currently landfills 200 wet tonnes of combined biosolids per day: 41% from primary effluent treatment; 21% from secondary effluent treatment, and 39% from deinking (wet basis). With landfill costs increasing, landfill space decreasing, and the development of odour problems, the PFPC is investigating other alternatives for biosolids utilization: 1) land application; 2) energy from waste; and 3) composting. The moisture content and C:N ratio of the combined biosolids are 67% and 48:1, respectively.

Nitrogen fertilizer costs to bring the C:N ratio to 40:1, the top of the suggested reasonable range for composting and land application would be approximately $36,400 annually. However, the most likely source of composting amendment at the PFPC is bark, which is readily available on site. At a mixture of 0.75 kg bark/kg biosolids, a moisture content of 60% and a C:N ratio of 90:1 results. Therefore, nitrogen addition costs to bring the C:N ratio of the mixture to 40:1 would be approximately $303,800 annually.

This study investigated the effect of C:N ratio on the composting of pulp and paper biosolids using bench-scale reactors, designed to simulate windrow composting. Four reactors (treatments) were run simultaneously, with C:N ratio's of 90:1 (control), 50:1, 30:1 and 20:1, each treatment was replicated three times. Each reactor was identical in mass, moisture content, particle size, amendments, loading, and aeration. Parameters that were monitored included compaction, temperature, and volatile solids reduction. It was found that an optimum C:N ratio (20:1) resulted in an increase in volatile solids reduction of 6% greater than the control (90:1), and showed similar temperature profiles. The results suggest that the added cost of nitrogen fertilizer may not be justified for increased composting performance. The C:N ratio therefore is not that important with respect to composting performance and can save millions of dollars annually in fertilizer costs, however there is a stability issue. The marketability of compost requires nitrogen addition to satisfy CCME Guidelines for Compost Quality. Nitrogen addition required to meet these guidelines would cost approximately $628,200 annually. Therefore more work is required in this area with long-term testing and phytotocicity tests.

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NOMENCLATURE AND ABBREVIATIONS

A	$\rightarrow$	area
BVS	$\rightarrow$	biodegradable fraction of volatile solids
CCME	$\rightarrow$	Canadian Council of Ministers of the Environment
C:N	$\rightarrow$	carbon to nitrogen ratio
Δ	$\rightarrow$	variability in the mean
d	$\rightarrow$	diameter
D_{db}	$\rightarrow$	dry bulk density
D_p	$\rightarrow$	particle density
D_w	$\rightarrow$	density of water
D_{wb}	$\rightarrow$	wet bulk density
FS	$\rightarrow$	fixed solids
h	$\rightarrow$	height
L	$\rightarrow$	total load
MC	$\rightarrow$	moisture content
n	$\rightarrow$	number of samples
n	$\rightarrow$	porosity
OC	$\rightarrow$	organic carbon
PFPC	$\rightarrow$	Pine Falls Paper Company Ltd.
S	$\rightarrow$	compressive stress
s	$\rightarrow$	standard deviation

s^2	$\rightarrow$	sample variance
s_x	$\rightarrow$	standard error
θ	$\rightarrow$	volumetric water content
t	$\rightarrow$	value obtained from a T table for a particular confidence limit
TKN	$\rightarrow$	total Kjeldahl nitrogen
TS	$\rightarrow$	total solids
V	$\rightarrow$	volume
VS	$\rightarrow$	volatile solids
x	$\rightarrow$	sample mean
x_i	$\rightarrow$	individual variable measurement

ACKNOWLEDGEMENTS

To Mom, Dad, & Jamie
Thank you for everything

CHAPTER 1

INTRODUCTION

In Canada it is estimated that approximately 500,000 dry metric tons of biosolids are produced each year. The total amount of biosolids requiring management has increased over the past several decades, thereby gradually increasing interest in the quality of biosolids and the potential for beneficial use (Gies 1995). Increased pressure on finding alternative means of disposal of sludge and biosolids from both industrial and municipal wastewater systems is world wide. In Canada, increased biosolids production, new environmental legislation, and closure of landfill sites affect municipalities, the agricultural industry, and, increasingly, the pulp and paper industry (Pickell and Wunderlich 1995). Gradually, traditional methods of sludge disposal by landfilling and incineration are being replaced by new disposal methods, methods that take advantage of at least one of the nutrient, soil conditioning, or fuel properties of sludge (Kuchenrither 1994). The most recent Canadian national survey of biosolids management was completed in 1981. Results indicate that of the total biosolids produced, 29 percent was being applied to agricultural land, 37 percent was being landfilled or incinerated, and the remaining 34 percent was assumed to be managed through temporary storage lagoons, followed by utilization and disposal. A 1992 survey of biosolids management in Ontario indicated that 18 percent of their total biosolids is applied to land, 27 percent is incinerated, and the remaining 55 percent is landfilled (Gies 1995). In the United states, the U.S. EPA estimates that of their total biosolids generated from sewage treatment plants, 49 percent are now being used for land application and other beneficial applications, 35 percent is disposed of by landfilling, and the remaining 15 percent is

disposed of by incineration (Pickell and Wunderlich 1995). Although the beneficial use of biosolids is gradually working its way into current disposal practices, the pulp and paper industry has been slow to react to these changes. Landfilling and incineration are still the most commonly utilized practices in this industry for a variety of reasons, including contaminant concerns, and cost concerns for transporting and hauling biosolids for land application (Table 1-1). Furthermore, even though alternatives such as land application appear to work effectively, many mills worry about future problems such as cost that may arise. For example, sites may have to be cleaned up at high cost due to water contamination (Scott and Smith 1995). Such factors have until recently deterred mills from investigating other alternatives, however, restrictive legislation, diminishing land availability, public opposition, and environmental problems are making landfilling less of a viable option (Pickell and Wunderlich 1995, Scott and Smith 1995). Also, many mills find the cost of constructing and operating an on-site landfill to be too expensive (Coburn and Dolan 1995, Scott and Smith 1995). As a result, beneficial use of biosolids is increasing through land application, composting, pelletization (Hepp and Wojichowski 1994) and other alternatives such as energy derivation (USEPA 1994a). The practice of using biosolids in a beneficial manner allows for the change from biosolids disposal to biosolids utilization. Such practices as land application of biosolids as a soil amendment or fertilizer supplement and various procedures that derive energy from biosolids or convert them to useful end products can help reduce the volume of biosolids requiring disposal, thereby reducing the rate at which the limited capacity of disposal facilities are exhausted. Other benefits derived from recycling biosolids include improved soil fertility and tilth, a reduction in the need for an enhanced response to inorganic fertilizers, better

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growth and quality of crops, and decreased consumption of energy (USEPA 1994a).

However, biosolids utilization alternatives which involve the development of new

products from pulp and paper sludge must ensure there is a market for the product in

order to be economically feasible. "It does not make sense to develop and create

products for which there is no market" (Scott and Smith 1995).

Table 1-1: Distribution of Current Pulp and Paper Mill Biosolids Disposal Practices
(Scott and Smith 1995).

Disposal Method	Mills Using Method (%)
Landfill	69
Incineration	27
Land Application	8
Other Methods	8

Residue from pulp and paper mills are discharged to the air in the form of gases, to the

water in the form of treated effluent (wastewater) and to land in the form of solid waste

and sludge (Figure 1-1). Air and water quality have significantly improved in the last

two decades, often the water being discharged is cleaner than the water taken in by the

mills. As these components are removed from the air and water discharge streams, a

greater amount of solid waste is produced and must be managed. Mills produce sludges

that are distinctly different in composition and a sludge utilization alternative must be based on the specific characteristics of a given sludge. Such utilization alternatives reduce the volume of material that is landfilled and recovers valuable materials such as nutrients and/or energy (Scott and Smith 1995).

Figure 1-1: Pulp and Paper Industry - Material Flow (Scott and Smith 1995).
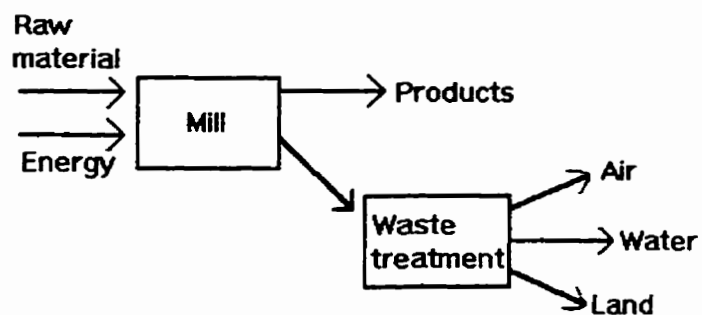
CHAPTER 2

PFPC BIOSOLIDS HISTORY

The Pine Falls Paper Company (PFPC), located 130 kilometers north of Winnipeg on Provincial Highway # 11 is Manitoba's only newsprint mill and Manitoba's largest recycler of old newspapers and magazines. This pulp and paper company has been operating since January 1927, over 70 years. Employing almost 500 people in their mill and woodlands operations, as well as an additional 600 seasonal contractors, the PFPC is committed to protecting and enhancing our natural environment and our surrounding communities. The company previously owned by Abitibi Price, was purchased by mill employees in September, 1994 after three years of negotiation. This newly purchased employee owned company is ready to undertake the enormous improvements and upgrades in strategic planning, especially in the area of safekeeping the environment. The dedication of PFPC to environmental stewardship becomes apparent in their vision statement, which includes the following: "The company's vision is to create and leave for future generations a world-class pulp and paper facility that operates in harmony with our social, economic, and environmental setting" (PFPC(a) 1995). The company was ISO (International Standards Organization) 9003 certified in July 1993 and continues to strive for excellence in environmental management and as such, accepts the responsibility of protecting the environment from any potential impact from its operation. A strong environmental policy is in place which addresses the mills compliance beyond legal requirements, environmental management, environmental planning, awareness promotion, training as well as other policy issues (PFPC(b) 1994).

Solid waste produced at the PFPC includes ash from boilers (coal ash), a small amount of concrete and construction material, general garbage and office wastes, bark, and sludge (biosolids) from treatment and deinking plants. 87000 tonnes of coal is used per year (241 tonnes/day) to fuel mill boilers at an ash content of 8-10%. Therefore, 22 tonnes of boiler ash is produced per day (@ an average of 9% ash content for coal) or 7824 tonnes of boiler ash per year for a 360 day working year. Historically the ash was transported to St. Georges landfill South East of the mill, but is now disposed of in the mills private landfill. The landfill was opened in the fall of 1995, and is located north of the Winnipeg River between the Maskwa River and Pine Creek. The small component of concrete and construction material is also disposed of in this landfill. St. Georges landfill site continues to be used for the disposal of garbage and office waste. Until the late 1950's, bark from the barking drums, which can't be used for pulp, was added to the effluent and flushed into the Winnipeg River. This resulted in a large bark accumulation that held water back. As a result a new boiler and bark handling system was developed to burn the bark and contribute to steam production for the mill. The ash produced from the bark (2.6% ash content) adds approximately 3.5 tonnes per day to the boiler ash. Reject material from screens and cleaners were sent to the clarifier in the woodroom and settled out as sludge. Approximately 10 tonnes of dewatered sludge was added to the bark per day to be burned in boilers. Waste oil from the paper machines was skimmed from effluent and burned in the refuse boiler. The remaining particles were carried to the Winnipeg River in the untreated effluent flow (MES 1995). Prior to December 1995, PFPC did not treat their process effluent, therefore no sludge was produced (Poetker MacLaren 1995).

In December 1995, a newly completed state-of-the-art waste water treatment facility came on-line, where all mill effluent is treated in a 40 hour process to purify all waste water from the mill (PFPC(a)). This wastewater treatment process was designed and constructed to do better than meet the strict federal and provincial environmental regulations and is continuously monitored for performance and quality. The mill is also equipped with contaminant dikes around process chemicals storage tanks so that these chemicals cannot enter the mill's sewer system and receiving waters (PFPC(b)). The wastewater treatment system employed at the PFPC is used to effectively treat mill effluent, however, as with any waste water treatment system there is a production of solid waste (biosolids). Of all the material entering the pulp and paper mills, an average of 35% becomes residue in the form of rejects (Scott and Smith 1995). The biosolids produced from the wastewater treatment facility is a combination of wastes from many different processing steps within the mill. The biosolids waste stream at the PFPC is composed of primary sludge, secondary (biological) sludge, as well as deink sludge. The deink sludge is produced as a result of treating the effluent from the recently completed (July 1996) deinking plant which recycles 150 tons of old newsprint and magazines daily, and was constructed at a cost of $36.5 million. In total, 200 plus tonnes of sludge (biosolids) are produced daily at 33 percent solids content (Sopuck 1997). PFPC has been aware of their need to effectively dispose of the biosolids in an environmentally appropriate manner long before effluent treatment processes were put on-line. Options that were considered included incineration, land application, and landfilling. Landfilling was selected, as a result over 200 tonnes of biosolids are transported each day from the mill to the new landfill at a cost of $600000 per year ($2000/day), with transportation

costs of $5.05 per tonne being responsible for approximately half of that total (Sopuck 1997). Recent local complaints of odour being produced from the landfill has caused the mill to employ clay caps for landfill cells. As well, a geosynthetic membrane will be used in the near future to help contain odours. This odour problem will result in costing the mill hundreds of thousands of dollars.

CHAPTER 3

IDENTIFICATION & DISCUSSION
OF UTILIZATION ALTERNATIVES

Landfilling has historically been used in the disposal of pulp and paper biosolids. In other jurisdictions the alternatives identified are: direct land application; energy from waste technologies; and composting and marketing (Hamilton and Laufenberg 1992; Wiegand and Unwin 1994). However, none of these technologies have been demonstrated at paper industries in Manitoba. The commercial utilization of the large quantities of sludges that are generated in the pulp and paper making process is the goal of every mill (Mick et al. 1982). However, since there is relatively little information on pulp and paper biosolids, much of the discussion within this chapter is based primarily on municipal biosolids.

3.1 LAND APPLICATION

As traditional sludge disposal methods gradually give way to beneficial use options, land application of biosolids appears to be the most widely implemented and notably accepted practice (Gies 1995; Pickell and Wunderlich 1995; Mjoberg et al. 1993). Years of extensive study and experience have provided a basis for government policies to promote the beneficial use of biosolids. As a basis for the safe use of biosolids, hundreds of studies have been conducted and thousands of publicly owned treatment works (POTWs) are currently using biosolids as an organic fertilizer and soil conditioner on land throughout North America (USEPA 1994a). Landspreading is an appealing technique because it represents a natural reuse and recycling of biosolids. Land application can

reduce the dependence on landfilling and be cost effective while maintaining a clean environment (Scott and Smith 1995).

3.1.1 LAND APPLICATION PROCESS

Land application of biosolids is the controlled application of biosolids to soil (USEPA 1983) through spreading, spraying, injection or incorporation of biosolids onto or below the surface of the land (USEPA 1994b; Nemeth 1982). Typically, the most common methods of application are surface spraying and direct injection (Gies 1995), however, an extreme variation of methods exist (USEPA 1983). Biosolids can be applied directly in liquid form, as a dewatered cake, or as composted or dried material. The application method will vary according to the nature of the biosolids, the type of terrain, the vegetation on the site, and the ultimate sludge use. However, common to all biosolids application systems is the need for stabilization and disinfection of the biosolids prior to land application. Therefore, digestion or other stabilization processes are often required, although in some cases, the biosolids may be stabilized as part of the wastewater treatment system (USEPA 1983). During seasonal variations of frozen ground, snow cover, spring thaw, and crop cover, biosolids are generally stored in lagoons or dedicated holding tanks (Gies 1995).

The primary purpose of land application is the ultimate disposal or recycle of biosolids which provides additional biosolids treatment and disposal in a single operation (USEPA 1983). However, land application also takes advantage of the soil enhancing qualities of the biosolids (USEPA 1994b). The effective application of biosolids can be used in agriculture, forestry, and land reclamation provided a suitable site with adequate

conditions exist. Major site conditions to be considered for the land application of sludge include:

- Soil type
- Slope
- Site susceptibility to flooding
- Depth to seasonal ground water table
- Permeability of the most restrictive soil layer
- Cropping patterns and vegetative cover
- Nutrient and organic matter content

Sludge loading rates are determined once a suitable application site has been selected and the process objectives are defined. The sludge loading rate is based on the most limiting constituent of those being considered, often nitrogen or phosphorus dictates the limiting rate to meet crop needs (USEPA 1983).

3.1.2 BENEFITS/DRAWBACKS OF LAND APPLICATION

Often more complex than the wastewater process itself is the handling, treatment and ultimately the disposal of biosolids in an environmentally acceptable and cost-effective manner. The practice of land application can not only serve as a cost-effective biosolids disposal technique, but can also serve land owners by improving soil characteristics, reduce fertilizer costs, and increase productivity (USEPA 1983).

The process of land applying biosolids often compares favorably against alternate biosolids utilization and disposal techniques where cost is concerned. This comparable

cost may be attributed to the fact that the land application process is not equipment oriented or energy intensive (USEPA 1983). Land application of biosolids can help eliminate or reduce the infrastructure and costs associated with burning process streams and eliminate or reduce the need for landfills (Macyk 1996). As an alternative to landfilling, land application of biosolids has been practiced for a number of years now, and appears to be economically viable (Tripepi et al. 1996). The use of biosolids in land reclamation efforts has proved very successful and comparable in cost to other commercial methods in both large- and small-scale projects (USEPA 1994a). Additional benefits of land application include recovering the costs of hauling and spreading from the sales of the biosolids to farmers (USEPA 1994a). Already a widely used process, land application frequently offers a practical and cost-effective disposal alternative (USEPA 1983), as discussed in chapter 3.1.3.

The largest difficulty concerning land application is finding enough land on which to spread the sludge. If a mill owns forest lands nearby, an ideal situation may exist. However, difficulties often arise when the land needs to be leased or other arrangements need to be made for spreading. Even a moderately sized mill would require a large area on which to spread. Therefore, for an average sized mill to use the amount of sludge that is produced, landspreading needs to be done on a relatively high volume basis (Scott and Smith 1995).

Biosolids are composed principally of organic matter which contains various levels of plant nutrients, water, and beneficial/detrimental organic and inorganic elements or compounds and organisms. In particular, wastes (biosolids) from pulp and paper operations have moderate nutrient levels, high organic matter levels, and low levels of

potentially deleterious compounds (Macyk 1996). Biosolids can be applied to land separately or in conjunction with chemical fertilizers to reduce the amount of chemical fertilizers required and enhance crop yields (USEPA 1994a). The application of sludge can benefit soils by reducing soil bulk density and surface crusting, as well as by increasing the soils water-holding capacity, humus content, cation exchange capacity, nutrients for plants, tilth, soil aeration and water aeration (Tripepi et al. 1996; Kuchenrither 1994; McGovern et al. 1982). The soils water retention, air exchange around plant roots, and the ability of the soil to hold nutrients in a plant available state (cation exchange capacity) are all improved by the biosolids ability to enhance soil rooting material, particularly in soils with low organic matter (USEPA 1994a). Such properties of nourishing, conditioning and buffering of the soil are reflected in the characteristics of pulp and paper biosolids (Scott and Smith 1995). Additional benefits of land application include the ability of biosolids to suppress pathogenic soil organisms such as nematodes that damage plant roots, and suppress specific plant root diseases that otherwise cause damage to commercially grown plants (USEPA 1994a). Biosolids are used in silviculture to increase forest productivity. Specifically, biosolids applied to forest land can shorten pulp wood and lumber production cycles by accelerating tree growth, especially on marginally productive soils. The U.S. Forest Service and the University of Washington have conducted studies on the use of biosolids as a fertilizer in silviculture. These studies have shown as much as a three-fold increase in tree growth compared to controls for certain tree species. Likewise, lands that have been harvested or disturbed by mining, construction, fires, land slides, or other natural disasters can be

revegetated and stabilized by biosolids application. Biosolids can also be used as a soil substitute for intermediate and final landfill cover (USEPA 1994a).

Biosolids are applied to improve soil structure and supply nutrients to vegetation grown in the soil of agricultural land, forestry land, reclamation sites, public contact sites, lawns and home gardens (USEPA 1994b). Although land application to plants can improve the soil physical properties while providing nutrients for growth, excessive sludge application can reduce crop yields (Kuchenrither 1994). The nutrient content of sludge must therefore be determined when considering land application, as must the nutrient requirements for a particular application. The biosolids must be characterized for a number of constituents and may include pathogens, phosphorus, nitrogen, as well as various heavy metals (USEPA 1983). When sludge is applied to soils at recommended rates it can supply all the needed nitrogen and phosphorus for good plant growth, as well as calcium, magnesium, and many essential micronutrients. The application of biosolids to land is often based on the amount on nitrogen a crop can use (excess nitrogen could leach below the root zone and contaminate groundwater). It is therefore necessary to determine the available nitrogen per ton of dry sludge solids.

$$\frac{\text{Available N}}{\text{tons of dry solids}} = 0.20\% \times N_1 + N_2 \qquad \text{(USEPA 1983)} \qquad [3\text{-}1]$$

where N = plant available nitrogen (%)
       N_1 = organic nitrogen (%)
       N_2 = NH_3-N and NO_x-N (%)

$$\text{Sludge application rate (dry tons/acre)} = \frac{\text{crop N requirements} - \text{residual N}}{\text{lb available N/ton sludge}} \qquad [3\text{-}2]$$

where crop N requirement = the lbs of N per acre recommended by the regulatory
agency
residual N = the lbs of N released per acre from sludge that has been applied in any of
the previous three years.

Phosphorus in sludges usually range from 0.1-1.7 percent, therefore the amount of phosphorus is often sufficient for plant growth when the sludge is applied at the nitrogen requirement rate. However, potassium levels in sludge typically range from 0.02-2.64 percent (median=0.30%), therefore sludges are usually deficient in potassium relative to crop needs (Kuchenrither 1994). With respect to the heavy metals content of a sludge, the concentration of various metals such as cadmium, copper, zinc, nickel and lead may restrict the land application of certain sludges containing these metals in concentrations equal to or greater than that permitted by federal, provincial and local regulations. Such limits are often based on the protection of food chain crops and considered by many to be conservative if used for non-food chain crops, thus serving to protect human and animal health (USEPA 1983).

Soil properties that affect the reactions and resultant plant uptake of sludge constituents include pH, organic matter, cation exchange capacity, iron and aluminium oxides, texture, aeration, specific sorption sites, and water availability. To predict the impact of sludge use on elemental content in the human diet, plant uptake of trace elements from sludge should be measured in field experiments. The trace element content of crops is a function of the plant available level in the soil and the modifying influences of soil chemical and physical properties. Information on background levels of metals in crops is needed to evaluate the impact of metals entering animal or human diet. The soil physical

properties are related to trace element uptake by plants. Estimation of food-chain transfer

is critical to valid estimation of the potential for risk. At the present, these estimates are

best made by considering:

- relative increase uptake of constituents by various crops from sludge-amended soil under responsive conditions

- the rate of ingestion of different crops by the population

- the demonstrated bioavailability of the increased amounts of an element in sludge-grown crops of ingested sludge

- an appropriate transfer coefficient from sludge-amended soil to edible crop tissues

Table 3-1 illustrates the pathways of exposure from land application of biosolids that can

be utilized in determining risk assessment. Grazing livestock ingest surface soil, this can

allow much more direct exposure to constituents in sludge than can occur via plant

uptake. Ingestion of sludge can allow exposure and/or risk which can be prevented by

incorporation of sludge below the soil surface, or by tilling sludge into the soil. To

minimize risk, wastewater treatment plants should identify the organics being discharged

by users, particularly industry. Risk assessments suggest that most sludge organics will

not increase the health risk to animals and humans (Page 1987).

Land application projects can be successfully implemented while avoiding potential

problems by following carefully planned procedures and using good management

techniques (USEPA 1983). Detailed and thorough planning is required for success. A

public education and participation program often help assure the success of a land

application project (USEPA 1983).

Table 3-1: Pathways of Exposure from Land Application of Biosolids (USEPA 1994a).

PATHWAY	DESCRIPTION
1. Biosolids-Soil-Plant-Human	Consumers in regions heavily affected by landspreading of biosolids
2. Biosolids-Soil-Plant-Human	Farmland converted to residential home garden five years after reaching maximum biosolids application
3. Biosolids-Soil-Human	Farmland converted to residential use five years after reaching maximum biosolids application with children ingesting biosolids-amended soil
4. Biosolids-Soil-Plant-Animal-Human	Households producing a major portion of their dietary consumption of animal products on biosolids-amended soil
5. Biosolids-Soil-Plant-Human	Households consuming livestock that ingest biosolids-amended soil while grazing
6. Biosolids-Soil-Plant-Animal	Livestock ingesting food or feed crop grown in biosolids-amended soil
7. Biosolids-Soil-Animal	Grazing livestock ingesting biosolids/soil
8. Biosolids-Soil-Plant	Crops grown on biosolids-amended soil
9. Biosolids-Soil-Soil Biota	Soil biota living in biosolids-amended soil
10. Biosolids-Soil-Soil Biota-Biota Predator	Animals eating soil biota living in biosolids-amended soil
11. Biosolids-Soil-Airborne Dust-Humans	Tractor operator exposed to dust from biosolids-amended soil
12. Biosolids-Soil-Surface Water/Fish-Humans	Humans eating fish and drinking water from watersheds draining biosolids-amended soils
13. Biosolids-Soil-Air-Human	Humans breathing fumes from any volatile pollutants in biosolids
14. Biosolids-Soil-Groundwater-Human	Humans drinking water from wells surrounded by biosolids-amended soils

3.1.3 LAND APPLICATION STUDIES

Statistics show that land application accounts for 8% of current biosolids disposal practices for pulp and paper mills (Scott and Smith 1995). This section of the report identifies and examines several land application studies of both municipal sludge as well as pulp and paper sludge.

Over 55% of all biosolids produced in Ohio are used on land. Likewise, over 90% of all biosolids produced in Maryland are used on land. Hannibal, MO (population 19 000), and Madison, WI (population 250 000) recycle their biosolids and charge farmers for using their biosolids. Hannibal recovers 100 percent of the hauling and spreading costs from its sale of biosolids to farmers. Madison fertilizes 3000 to 4000 acres of farmland per year and has 22000 acres of farmland available by farmers waiting for application. Madison receives $12 (U.S. 1994 currency) per acre for applying their biosolids (USEPA 1994a). Seattle, WA (population 1.1 million) also recycles their biosolids by applying it to forest as well as agricultural land (USEPA 1994a), Seattle is said to have been one of the first to use biosolids in forestry (Pickell and Wunderlich 1995). All biosolids produced in metropolitan Washington, DC (population 3 million) have been used on land since 1974. In 1993, approximately 75 percent (87 000 dry tons) of the dewatered biosolids produced was used on agricultural land in Maryland (4000 acres) and Virginia (4000 acres). The remaining 25 percent was composted and used by horticulturists, landscapers, and the general public. At no charge to the farmers, the dewatered biosolids were applied to private farmland by private contractors. From each 5 to 10 dry ton per acre application of biosolids, the farmers received $100 to $140 (U.S. 1994 currency) worth of needed nitrogen, phosphorus, trace nutrients, lime, and organic matter (USEPA 1994a).

Biosolids have proved to be successful in land reclaimation efforts in both large- and small-scale projects. A land reclaimation using municipal biosolids in Fulton County, IL cost $3700 (U.S. 1994 currency) per acre as compared with a range of $3400 to $6300 (U.S. 1994 currency) per acre using commercial methods. Studies in Colorado

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demonstrate that biosolids applied to range land improve range quality and reduce water runoff proportional to the rate of biosolids application. In New Mexico, studies show the application of biosolids to range land improve growth and nutritional quality of desirable native vegetation, and reduced run-off of rain water from a one-time, 10 to 20 dry tons per acre surface application. In Pennsylvania, biosolids have been used to reclaim over 3000 acres of lands devastated by mining and smelting activities. A Palmerton, PA, site was highly contaminated where all vegetation in surrounding area was destroyed from 90 years of smelting zinc. This site was reclaimed using a combination of fly ash and biosolids to revegetate soils (USEPA 1994a).

A project of land application was conducted by the Greater Vancouver Regional District (GVRD), Western Forest Products Ltd., and IBEC Aquaculture in 1990. Various mixtures of sewage sludge, pulp mill wastes, and fish mort silage were applied to forest sites in southern British Columbia, near Port McNeill on Vancouver Island. Results indicate a rapid response by young conifers to organic fertilization (Pickell and Wunderlich 1995).

In 1992 a project of biosolids application was completed at Malaspina College (British Columbia) that was co-sponsored by Nutrifor. 600 dry tonnes (2500 wet tonnes) were applied over an area of 26 hectares in the Malaspina College Research forest on central Vancouver Island. Three application techniques were investigated: hand spray; wet application; and dry application. Full-scale projections were made using data obtained from the trial to estimate the cost per tonne of sludge for each application method. Dry application appeared to have the lowest cost of the three methods investigated, as it eliminates the need to re-wet the sludge (Pickell and Wunderlich 1995).

In the last 10 years, much work has been done with land application of pulp and paper mill sludge. The company QUNO Inc., from Thorold, ON, has over 6 years of experience with land application of primary, secondary and de-inking sludges in Ontario. Generally, primary and de-inking sludges have similar characteristics with low nitrogen and high fiber content. Secondary sludges on the other hand generally have relatively high nitrogen and phosphorus content and low fiber content. Therefore the secondary sludges are more suitable for land application, this can be attributed to a higher nutrient value. The heavy metal content of the combined paper mill sludge was found to be equivalent to that of cattle manure, and about one tenth that of municipal sludge. The sludge has been successfully used as a replacement for manure in agricultural applications and land reclamation projects of old coal/clinker sites, sand pits and a former foundry site (Pickell and Wunderlich 1995).

A program of land application exists in the Region of Niagara. The region has 10 water pollution control plants that treat approximately 20 billion gallons of sewage per year (54 million gallons per day). From that, approximately 13000 dry metric tons of biosolids are produced per year and applied to land in liquid form. The biosolids must by law be a consistent, stabilized, high quality product. The solids are anaerobically digested and can be applied to land between April 1 and November 30, as weather and crop schedules allow. The anaerobically digested biosolids are stored during the non-application season. All biosolids are applied through sub-surface injection at a total program cost of about $150 (Canadian currency) per dry metric ton over a five year contract. Sewage sludge is not the only organic material directed to land application, other material include grape pomace, compost, poultry litter, processing residuals and paper mill sludge (Gies 1995).

A study was conducted by Domtar Specialty Paper at Cornwall, ON, in the early 1990's to investigate the use of primary paper mill sludge as a herbicide-substitute/mulch layer in forest plantations to control weed growth. Residue analysis indicate mainly waste fiber and lime which are potential renewable resources for forest application. As weed control is of critical importance in hybrid poplar culture, a mulching material is required to provide an inert cover to suppress weed growth during the initial growth periods of trees and eventually decompose into nutrients with no negative impact on soil and water quality or tree growth. Test plots were used to conduct trials on a 3.5 hectare plot near the mill. "The objectives of the trial were to: demonstrate that primary clarifier sludge can be used as an effective herbicide substitute during the growth of hybrid poplars; observe the decomposition of the mulching materials over the years; assess the chemical and physical impact on soil properties; and evaluate plant response to the application." Results of this study show that the primary clarifier fiber was effective in controlling weed control. Compared to non-treated plots, suppression of weed growth was in the range of 75 to 90 percent. It was also found that sludge applied with a 10 centimeter thickness was equally effective as sludge applied with a 20 centimeter thickness for controlling weed growth, therefore, thickness of application had no affect on weed growth suppression. Also, the sludge spread in 1992 remained as effective as the fresh sludge spread in 1994. The reason the primary clarifier sludge serves as such a good inert cover to suppress weed growth is due to its high carbon to nitrogen ratio. Over time the sludge accumulates nitrogen and the carbon to nitrogen ratio decreases, thereby increasing the sludge degradation rate, hence the effectiveness of the sludge as a mulching material is anticipated to decrease. The study also indicates that the application

of sludge entails no negative impact on tree growth, provided that poplar cuttings have adequate contact with the soil. The sludge applied plots did in fact show indications of improved tree growth. As far as soil properties are concerned, the application of sludge had a negligible effect (Lo et al. 1996).

A cooperative effort involving industry, Canadian federal, and provincial funding agencies and the Alberta Research Council have been researching the use of pulp & paper biosolids in landspreading since 1991. The objectives of the research programs was to characterize mill waste and assess the effect of landspreading. These objectives were designed to provide data to industry, government regulators, and the general public in order to promote the landspreading of pulp mill wastes on forest and agricultural land, and in particular to provide a clear understanding of the "implications/benefits" of such practices. Research activities included a literature review, process stream characterization, greenhouse pot experiments, growth chamber experiments, column leaching experiments, and field landspreading trials. Field experiments show that the application of pulp mill sludge is beneficial on grass yields and that the grass yields increased proportionally to increase in sludge application rates. With the decomposition of the biosolids, the nutrients were released over a period of at least three to four years, thereby improving the moisture holding capacity of the amended soil, and benefiting plant nutrition and protecting groundwater quality. Also, the seedling grown in the biosolids amended soil had a deeper green color and a healthier appearance than the control seedlings, indicating greater tree health and vigor. Biosolids application had a significant beneficial effect on the physical properties of the amended soils, including a decrease in bulk density and an increase in moisture availability with increasing biosolids

application rate. Conclusions from this research indicate that conventional and deink sludges are beneficial soil amendments and can be applied at environmentally acceptable rates of 40 dry tonnes/ha to 80 dry tonnes/ha depending on the characteristics of the sludge and the soil. It is also recommended that multiple applications of sludge be considered at a rate of either 50 dry tonnes/ha every two to three years or 80 dry tonnes/ha every four years. These application rates "should be environmentally acceptable, provided that the area is supporting annual crops, forage or pasture" (Macyk 1996).

A study relative to the use of pulp & paper sludge used for agricultural applications was conducted at the university of Idaho. The research investigated the use of raw and composted paper sludge as a soil additive or mulch for cottonwood plants. Under greenhouse conditions, the effects of the sludge mixtures, application rate, method of application and plant clone on the growth of cottonwood cuttings and soil characteristics were determined. The mixtures of both the raw and composted sludge had similar characteristics, however the C:N ratio of the composted sludge was 32:1 as compared with 107:1 for the raw sludge. Throughout the study, cottonwood plants grew well in both soil treated with raw or composted pulp & paper mill sludge and paper sludge mixtures. The stem diameter of the cottonwood plants increased as sludge application rates increased, this relationship followed a linear relationship then a curvilinear relationship at greater application rates. The stem diameters of the plants amended with the raw sludge mixture were generally larger than those treated with compost. As sludge application rate increased, the height of the cottonwood plants also increased in a linear and curvilinear manner. Generally, the plants treated with raw sludge grew taller than

those treated with compost, and the plants mulched with sludge grew taller than the plants grown in sludge-amended soil. This study concluded that the growth of young cottonwood plants was improved with the use of raw and composted pulp & paper sludge under greenhouse conditions, where the sludge is applied as mulch or incorporated into the soil. The sludge provides mineral nutrients and improves water retention in the soil, therefore improving plant growth. Based on this research and economic considerations for composting and material application, the use of a raw sludge mixture applied as mulch in cottonwood plantations may be the most effective method of using kraft pulp & paper sludge (Tripepi et al. 1996).

3.2   ENERGY FROM BIOSOLIDS

Due to environmental problems that need solutions, favorable legislation, and combinations of both, biofuel usage has slowly increased over the last several years. As a result, biofuels markets exist and they are large. Less than 1 percent of the annual biomass growth is utilized for energy worldwide, however, biomass provides 15 percent of the total primary energy consumption. Biomass energy is a commodity and clearly occupies an important position in commerce (Klass 1990).

The waste stream of the pulp and paper industry is typically landfilled (Kraft and Orender 1991), and although not widespread, the practice of burning sludge associated with pulp and paper manufacturing plants is a common one (Someshwar et al. 1990). Of the material entering the pulp and paper mills, approximately 35 percent becomes residue in the forms of rejects. Some of these residues currently provide 56 percent of the energy needs of the industry. Incineration decreases the volume of material that is landfilled and

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recovers energy from sludge. Incineration takes various forms and is the most common alternative in the pulp and paper industry after landfilling (Scott and Smith 1995).

Wastes can typically be thought of as the combination of semimoist combustible and noncombustible materials (Tchobanoglous et al. 1993). "Sludge can be easy to burn with the right combustion technology", where the technology is fuel specific (Kraft and Orender 1991). There are four important properties that must be known if solid wastes are to be used as fuel: Proximate analysis; Fusing point of ash; Ultimate analysis; and Energy content. Proximate analysis involves testing for moisture, volatile combustible matter, fixed carbon, and ash. The fusing point of ash is the temperature at which the ash resulting from the burning of waste will form a solid clinker by fusion and agglomeration. The ultimate analysis is the determination of major elements as a percent, typically carbon, hydrogen, oxygen, nitrogen, sulfur, ash and often halogens. Energy content of wastes can be determined using calorimeters and by calculation (Tchobanoglous et al. 1993).

3.2.1 THERMAL PROCESSES

Energy recovery covers a wide range of technologies (Scott and Smith 1995). There are three principal chemical processes for the thermal conversion of solid waste, these include pyrolysis, gasification, and combustion (chemical oxidation). Pyrolysis is a endothermic process in which organic material is split in an oxygen free atmosphere through a combination of thermal cracking and condensation reactions into gaseous, liquid, and solid fractions, theoretically the most efficient system available (Board 1986). End products can either be a gas stream containing mainly hydrogen (H_2), methane

(CH₄), carbon monoxide (CO), carbon dioxide (CO_2), and other gases, or a tar and/or oil stream or a char consisting of almost pure carbon. Although pyrolysis is widely used in industrial processes, the pyrolysis of solid waste has not been very successful. Reasons for this failure in the past may be attributed to the inherent complexity of the systems and lack of appreciation by system designers of the difficulties of producing a consistent feedstock. Also, if gaseous fuels are desired, a simpler and more cost-effective technology would be gasification (Tchobanoglous et al. 1993). The conversion of biomass to gaseous fuels is known as gasification (Klass 1990). Gasification consists of the partial combustion of a carbonaceous fuel. As a result, a combustible fuel gas rich in saturated hydrocarbons (methane), hydrogen and carbon monoxide is produced and can be combusted in a boiler or internal combustion engine (Durai-Swamy et al. 1991). Air-blown gasifier operation is a very stable process in which a fairly constant quality of gas is produced over a broad range of air input rates. The gas produced has an energy content which can be increased by as much as two fold with the use of pure oxygen as an oxidant instead of air. There are five types of gasifiers used in gasification, these include vertical fixed bed gasifiers, horizontal fixed bed gasifiers, fluidized bed gasifiers, multiple hearth gasifiers and rotary kiln gasifiers. Of these, the first three types are the most widely used. Advantages of the vertical fixed bed gasifier over other gasifier types include simplicity and relatively low capital costs. However, one drawback is the sensitivity of the vertical fixed bed gasifier to mechanical characteristics of the fuel, which must be uniform and homogeneous. "Gasifiers have the potential to achieve low air pollution emissions with simplified air pollution control devices" (Tchobanoglous et al. 1993). The conversion of biomass to heat, steam or electric power is achieved by combustion processes. A wide

range of equipment is available, the specific types employed depend on the scale of operation, feedstock characteristics, and desired energy products. Combustion is the chemical reaction of oxygen with organic matter where oxidized compounds, light and heat are produced. To ensure a complete reaction, excess air is used resulting in the following end products: nitrogen gas (N_2); carbon dioxide (CO_2); water (H_2O, flue gas). oxygen (O_2); small amounts of trace gases; and noncombustible residue. This reaction can be represented as follows (Tchobanoglous et al. 1993):

$$oganic\ matter + excess\ air \rightarrow N_2 + CO_2 + H_2O + O_2 + ash + heat \qquad [3\text{-}3]$$
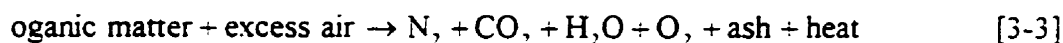
Figure 3-1 illustrates a typical continuous-feed combustor for the production of energy

Figure 3-1. Typical Continuous-Feed Combustor for the Production of Energy (Tchobanoglous et al. 1993).
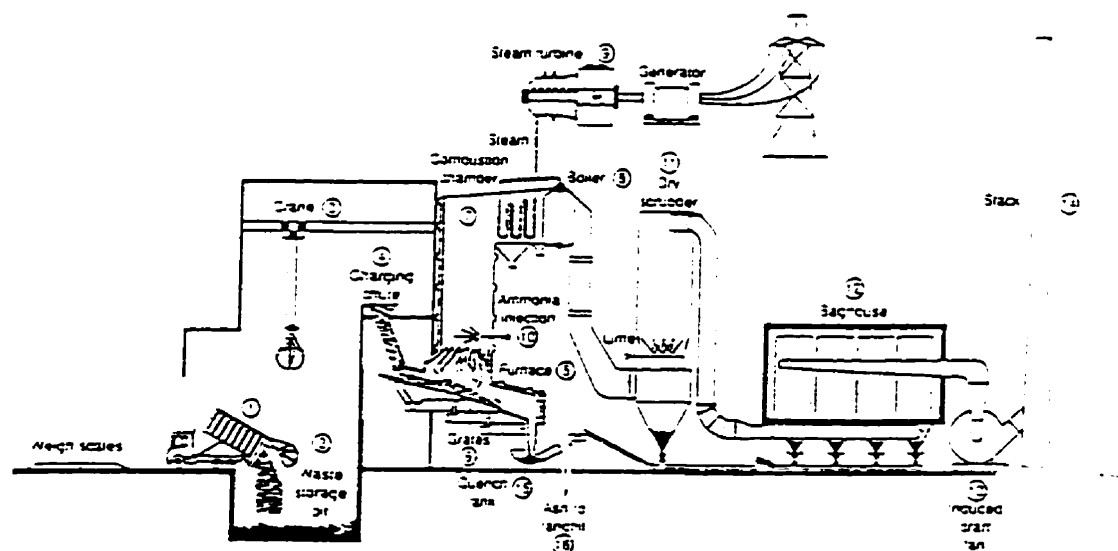
As with any combustion process, time, temperature, and turbulence drive the process. The fuel particle must absorb heat to elevate its temperature to the ignition point. Air must surround the fuel as the oxygen availability sets the combustion rate. Good mixing (turbulence) assures a continuous oxygen supply, therefore a rapid combustion rate. There must also be adequate time allowed for combustion to occur (Kraft and Orender 1991). Five issues must be considered with the combustion process, these include siting, air emissions, disposal of residuals, liquid emissions and economics (Tchobanoglous et al. 1993).

Conventional combustion is often carried out using the travelling grate combustion process. The travelling grate combustion process is a common method for burning sludge where sludge is co-fired with bark using an existing power boiler (Scott and Smith 1995). However, sludge is more difficult to burn than bark. The combustion process for a travelling grate power boiler depends on: a uniform layer of fuel on the grate, good air distribution (turbulence); a source of heat to ignite the fuel particle (temperature), and; an optimum grate speed for complete combustion (time). Radiation is the primary mode of heat transfer. Radiant heat transfer is a direct function of temperature (Kraft and Orender 1991).

$$Q = f(T_2^4 - T_1^4) \hspace{3cm} [3\text{-}4]$$

where Q = radiant heat transfer
  T_2 = combustion zone temperature
  T_1 = fuel particle temperature

Since Q is a function of temperature raised to the 4th power, a small decrease in T_2 can result in a large decrease in Q.

To successfully burn sludge in a traveling grate boiler one must understand the difference between sludge and bark (Table 3-2). Major differences between sludge and bark are ash contents ranging from 20.22% - 0.2%, oxygen contents ranging from 7.91% - 21.55%, and "as fired" Higher Heating Values (HHV) ranging from 5043 KJ/Kg - 10422 KJ/Kg. For the traveling grate combustion process, up to 20 percent sludge can be burned (Kraft and Orender 1991).

Table 3-2: Sludge and Bark Analysis (sludge analysis normalized to 58% moisture content (Kraft and Orender 1991).

% By Weight	1 Deinking Sludge	2 Deinking Sludge	3 Pulp Mill Sludge	4 Bark
Moisture	58.00	58.00	58.00	50.00
Carbon	12.10	13.07	21.66	25.15
Hydrogen	1.48	1.83	2.40	3.10
Nitrogen	0.22	0.36	0.40	--
Sulfur	0.07	0.08	0.39	--
Ash	20.22	14.00	4.86	0.20
Oxygen	7.91	12.66	12.29	21.55
	100.0	100.0	100.0	100.0
HHV Wet (Btu/lb)	2170	2208	3885	4485
HHV Dry (Btu/lb)	5167	5257	9250	8970
Theoretical Air (lb/10KB)	7.217	7.217	7.234	6.77
HHV Wet (KJ/Kg)	5043	5131	9028	10422
HHV Dry (KJ/Kg)	12007	12216	21495	20844
Theoretical Air (KJ/Kg)	3.11	3.11	3.12	2.92

An alternative design to conventional combustion is fluidized bed combustion (FBC) (Tchobanoglous et al 1993), which has proven to be most advantageous in many cases (Meckel et al. 1996). A fluidized bed boiler can be used if sludge is added to an already wet bark or 100 percent sludge is wanted to be burned (Scott and Smith 1995). Fluidized

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bed boilers allow for successful burning at significantly lower combustion temperatures than conventional boilers (760°C - 904°C) (Kraft and Orender 1991, and Scott and Smith 1995). In a fluidized bed boiler, heat transfer remains high as long as bed temperature is maintained, unlike a travelling grate. For some fuels such as bark and coal, the heat released by the fuel is in excess to the amount of heat given up by the bed material to ignite the fuel. For other fuels (sewage sludge) with moisture contents that exceed 65 percent, the bed material must give up more heat to evaporate the moisture than is given back to the bed by the fuels heat. For some fuels such as pulp sludge, the amount of heat given up by the bed to evaporate moisture and heat the fuel particle to ignition equals the heat given up by the fuel (Kraft and Orender 1991). Depending on the Higher Heating Value (HHV) and ash content of the sludge, this typically occurs at 58 to 62 percent moisture. Therefore if the fluidized bed is to burn mainly sludge or only sludge, the sludge-only/sludge-bark must be dewatered to a moisture content of 58 to 62 percent where no in-bed surface is required (Kraft and Orender 1991, and Scott and Smith 1995). Figure 3-2 illustrates a typical fluidized bed combustion system for refuse-derived fuel. This system consists of a vertical steel cylinder with a sand bed and air injection nozzles called tuyeres. Air is forced through the tuyeres thereby fluidizing the bed and expanding up to twice its resting volume. Solid fuels are injected into the fluidized bed where turbulence and mixing transfers heat to the fuel (Tchobanoglous et al. 1993).

Figure 3-2: Typical Fluidized bed system for Refuse Derived Fuel (Tchobanoglous et al. 1993).
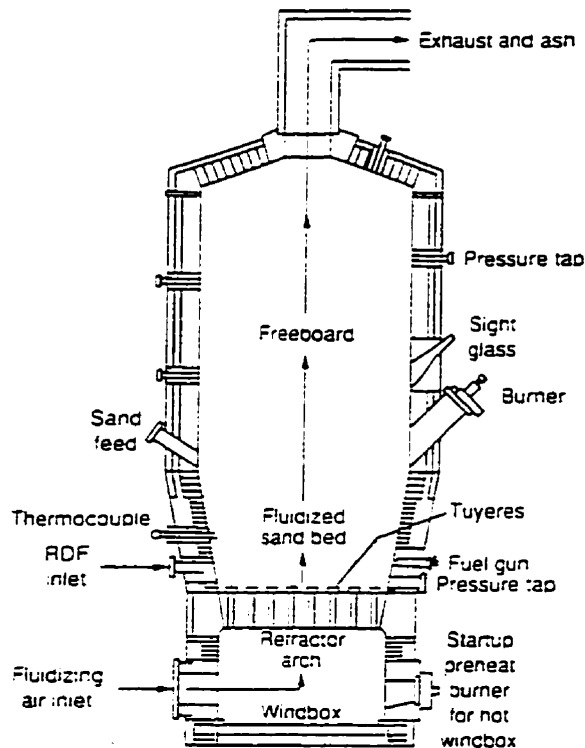
A circulating fluid bed can be used when necessary to burn sludge with high quantities of coal, bark, or a high energy fuel (Kraft and Orender 1991). A circulating fluid bed avoids the use of an in-bed surface by removing some of the hot bed material. This is done because more heat is produced than is needed for evaporation and heating when sludge is burned with large amounts of bark coal, or other high energy solid fuels. (Scott and Smith 1995).

Combustion characteristics will vary from sludge to sludge (Pepperman 1991). Steam produced through thermal processes can be converted to mechanical or electrical energy or be used directly for industrial processes or building heating (Tchobanoglous et al.

1993). Energy can be recovered by the use of a water-wall combustion chamber or by the use of waste heat boilers, whereby either hot water or steam can be generated. Generated steam can be used for heating and generating electricity (Figure 3-3) while hot water can be used for heating applications (Tchobanoglous et al. 1993).

Figure 3-3: Energy Recovery System (Tchobanoglous et al. 1993).

Steam from shredded and classified solid wastes, or solid fuel pellets fired directly in boiler, or from solid wastes mass fired in water-wall boiler. With mass-fired units auxiliary fuel may be required.
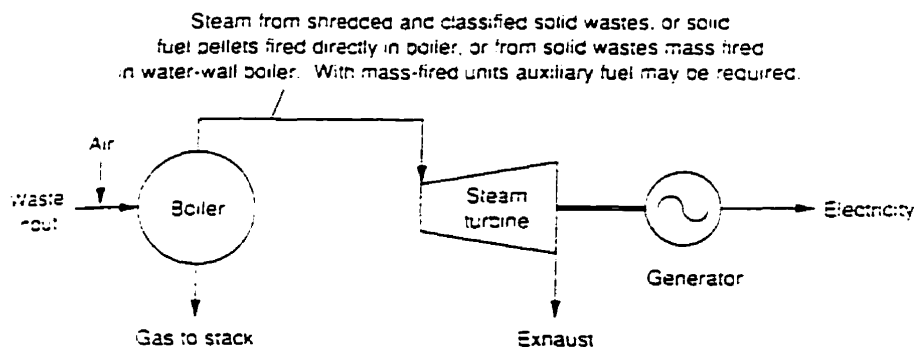
For the water-wall combustion chamber, the walls of the chamber are lined with boiler tubes in vertical continuous sections. Steam is generated as water is circulated through the tubes absorbing heat generated in the combustion chamber. For waste heat boilers, hot flue gases are passed through a separate boiler separate from the combustion chamber (Figure 3-4). The combustion chamber is lined with insulating refractory materials to reduce heat loss through furnace walls (Tchobanoglous et al. 1993).

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Figure 3-4: Waste Heat Boiler for Heat Recovery (Tchobanoglous et al. 1993).
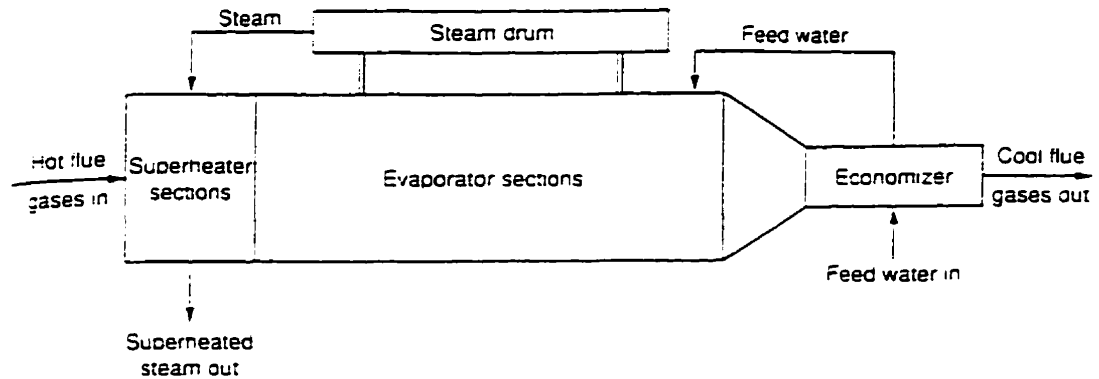
"High-organic, low-moisture sludges are good candidates for incineration" (Scott and Smith 1995).

3.2.2 ENVIRONMENTAL CONTROL SYSTEMS

Several impacts affect the environment as a result of thermal recovery systems. These environmental impacts include gaseous and particulate emissions, solid residuals, and liquid effluents. The critical part of the design of thermal processing systems is often in accounting for emission control. Air pollution control is a major concern in the implementation of such a process (Tchobanoglous et al. 1993; Gullichsen 1993).

Air emission pollutants include particulate matter, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ozone (O_3), and metals such as lead (Pb). These pollutants at various concentrations can cause adverse effects on humans and the

environment. Particulate matter can be inhaled causing health problems, carbon monoxide can cause a lack of oxygen in the human body resulting in headaches, nausea, and even death. Nitrogen oxides contribute to the formation of acid fog and rain, sulfur dioxide can cause illness or death where symptoms include irritation of the eyes, nose and throat (Tchobanoglous et al. 1993; Aghamohammadi and Durai-Swamy 1993). Along with incineration emission concerns involving NO_x and SO_2 (acid rain) gases, chlorinated compounds found in plastics that contaminate the paper can also be problematic (Scott and Smith 1995).

There are five classes of control equipment for gaseous and particulate air emissions from resource recovery systems:

- electrostatic precipitators, fabric filters, electrostatic gravel bed filters

- source separation, combustion controls, flue gas treatment (NO_x control)

- source separation, wet or dry scrubbing (SO_2 and acid gas control)

- combustion controls (CO & HC control)

- source separation, combustion controls, particulate control (non criteria pollutant controls)

The removal efficiency of air pollutant control equipment can be calculated using the following formula:

$$E = \frac{W_{inlet} - W_{outlet}}{W_{inlet}} \times 100\% \qquad [3\text{-}5]$$

where E = collection efficiency (%)
  W_{inlet} = pollutant inlet weight
  W_{outlet} = pollutant outlet weight

When sludge is displacing bark in a bark fired boiler, N, S, and ash increase, as a result there is an increase in NO_x emissions. Pulp mill sludge which is burned is a major contributor of sulfur pollution. Ash contents of sludge are greater than bark, this results in an increase in particulate emissions. The overall impact depends on the amount of bark that is displaced by the sludge. The amount of sludge that can be burned is often set by existing air permits and not the equipment's inability to burn more sludge (Kraft and Orender 1991). Gaseous pollutants require extraordinary means to meet the output level required. The ability to meet various gaseous emission levels is a priority (Rode 1991). However, air pollution impacts should not eliminate thermal processing options from consideration, as high efficiency emission control equipment can be employed (Jones et al. 1976). Solid residuals produced from thermal processes include bottom ash, fly ash and scrubber product. Bottom ash is the unburned and nonburnable portion of the material being burned. Bottom ash from most combustion systems is landfilled without processing. Fly ash, or particulates are removed from flue gases using filters, etc. Fly ash must be handled carefully to avoid fugitive dust emissions. Scrubber product is the material produced by scrubbers and can result in solid or liquid wasted depending on the type of scrubber used (Tchobanoglous et al. 1993).

Wastewater results from several sources in the energy from biosolids processes including wet scrubber effluent and wastewater from boiler feedwater production. The quantities of wastewater produced are relatively minor compared to the leachate produced from a landfill. Such wastewater may require treatment (Tchobanoglous et al. 1993).

"Burning sludge has an environmental impact" (Table 3-3) (Kraft and Orender 1991). "When considering burning sludge, it is important to consider how close you are to the

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emission limits. It may not necessarily be the boiler equipment that cannot handle the sludge, but the emission requirements" (Scott and Smith 1995).

Table 3-3: Elements Contributing to Major Pollutants (Kraft and Orender 1991).

Element	Deinking Sludge	Pulp Sludge	Bark
N₂ lb/MKB (g/MJ)	1.63 (0.737)	1.03 (0.466)	0.89 (0.403) (N₂=0.4%)
S lb/MKB (g/MJ)	0.36 (0.163)	1.00 (0.452)	---
Ash lb/MKB (g/MJ)	63.4 (28.7)	12.51 (5.7)	0.45 (0.204)

3.2.3 DRYING

As biological solids generated in wastewater treatment become more common, combined mill sludges have become more difficult to dewater. Mills are searching for a way to: reduce the costs associated with sludge hauling; get maximum use out of existing landfill space, and; make sludge a more attractive fuel for combination-fuel-fired boilers. Therefore, there is a growing interest among pulp and paper companies in sludge dewatering technologies capable of producing drier cakes at a reasonable cost. Mechanical dewatering methods are rarely able to reduce the water content of sludges below 60 percent. Modern sludge-drying systems vary considerably, some drying equipment used by pulp and paper mills include but are not limited to: dedicated gas-fired rotary kiln dryers to dry particularly wet and difficult-to-dewater waste treatment sludge; gas- or oil-fired air-entrained dryers; drying sludge while being conveyed by boiler flue gas through pneumatic hog-fuel transport systems; wood fuel drying systems, and; the Carver-Greenfield process (multieffect or mechanical vapour recompression evaporation with the use of a fluidizing carrier oil). "The most appropriate technique to

dry high moisture pulp and paper sludges to very low moisture contents (≤ 10%) appears to be a technically proven heavy oil version of the Carver-Greenfield process, operating at drying temperatures of up to 115°C" (Azarniouch 1995). A modern screw press can increase the solids content of clarifier sludge to 45-50% on a continuous basis (Linderoth 1989).

Dried sludge may be utilized as a fuel source. The costs of energy are a critical factor in the economics associated with drying sludge. It has been demonstrated on both the pilot and commercial scale that dried sludge is suitable for use as a fuel (Pepperman 1991). Vesilind and Ramsey have conducted research to determine the effect of drying temperature on the final heating value of sludge. Results indicate that for temperatures in excess of 105°C, the Higher Heating Value (HHV) of dried sludge is dependant upon the temperature to which it is exposed prior to the measurement of the heat value. Also, little volatile matter is lost until 80 - 90 percent of the original moisture content of the sludge has evaporated, regardless of the temperature of heating. Higher Heating Values (HHV's) for sludge samples tested were strongly influenced by the temperature under which they were dried (Figure 3-5). Also, little , if any, chemical energy is lost at drying temperatures between 25 - 105°C (Vesilind and Ramsey 1996).

Odour problems during storage and handling are virtually eliminated through drying (Hordesty and Beer 1993).

Figure 3-5: Higher Heating Values (HHV's) at Various Drying Temperatures for Sludge Samples (each data point represents the average of three experiments) (Vesilind and Ramsey).
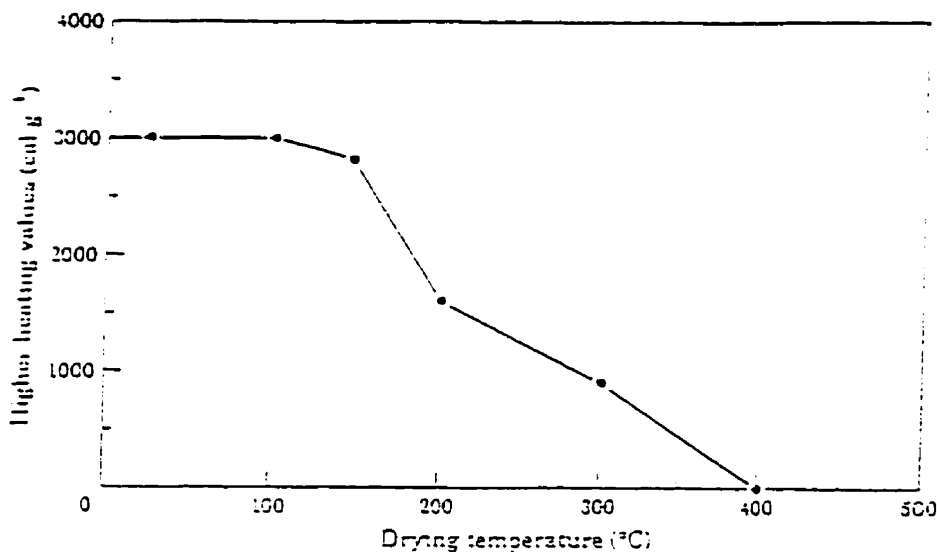
3.2.4 BENEFITS/DRAWBACKS OF ENERGY FROM BIOSOLIDS

The purpose of thermal conversion of solid waste is to both reduce the volume of the waste and/or to recover conversion products (Tchobanoglous et al. 1993). Biomass fuels have been burned in stoker fired steam generators for years. They provide a relatively inexpensive fuel source (Rode 1991). Traditional burning shifts some of the pulp and paper industries residue to the air discharge stream with its resulting costs and problems. However, "we must not shift the problem from land to air". Therefore, major drawbacks to incineration include large capital investments as well as stringent pollution control requirements, and due to low fuel values, incineration is often not cost effective. In order

to justify the large capital expenditure for incineration, the economics of the process must be considered. Such considerations should include (Scott and Smith 1995):

- the need for supplementary fuel to sustain combustion
- ash handling and disposal
- sludge dewatering capacity
- the efficiency of existing boilers

Combustion is the most commonly used of the chemical transformation processes due to its ability to recover energy in the form of heat. The use of a combustion system results in a reduction in volume of waste as well as energy recovery which can help to offset operating costs and reduce the capital costs of air pollution control equipment (Tchobanoglous et al. 1993).

For the travelling grate combustion process there are obvious advantages such as simplicity and the ability to use existing boilers, however, there are also a number of drawbacks and problems with such a system (Scott and Smith 1995). Due to the difference in ash and oxygen content between sludge and bark, sludge is more difficult to burn than bark (Kraft and Orender 1991, and Scott and Smith 1995). As the amount of ash increases, the flue gas weight increases while the total heat available remains constant. As a result, the enthalpy of the flue gas decreases (Kraft and Orender 1991).

$$h = \frac{heat}{mass} = \frac{total\ heat\ available}{flue\ gas\ weight} \qquad [3\text{-}6]$$

Therefore, a high ash content can increase the heating load of the boiler and therefore reduce efficiency. High ash is detrimental to the heating value of sludge, often deinking

sludge has a greater ash content than primary and secondary sludge (Scott and Smith 1995). Sludge requires more air than does bark, in order to release the same amount of heat. This is due to the lower oxygen content in the sludge. This extra air that is required dilutes the flue gas with extra cooler air, thereby lowering combustion zone temperatures (Kraft and Orender 1991). Also the moisture content of sludge is greater than that of bark, therefore moisture tends to increase in the boiler lowering the combustion temperature. An increase in moisture content of 1 percent will cause a decrease in combustion temperature of 10°C, resulting in a decrease in heat transfer of 13143 Btu/hr*ft^2 (Kraft and Orender 1991, and Scott and Smith 1995). To compensate for moisture content and oxygen, the moisture content would need to be lowered to produce the same combustion zone temperature as bark alone. Some equipment evaluations to consider are: raise the combustion air temperature by removing economizer surface and adding air-heater surface; for continuous stream sludge addition, cover the lower furnace walls with refractory material; dewater the sludge to a higher solids content, and; install a mechanical mixer upstream of the fuel conveyor belt to better mix bark and sludge (Kraft and Orender 1991). Mixing may be necessary because the uniformity of the feed is very important to maintain boiler temperature. Due to moisture and other operating conditions, the amount of sludge that can be co-fired may be limited (Scott and Smith 1995). Sludge is difficult to burn due to its high ash and moisture contents and low heating values. (Kraft and Orender 1991).

Travelling grate combustion has moisture limits due to evaporation and its effect on combustion temperature, therefore a fluidized bed system may be used (Kraft and Orender 1991). This fluidized bed process is also more environmentally friendly than

other waste to energy processes. For the fluidized bed process, if the moisture content is too high, supplemental fuel may be needed. Fluidized bed has been found by some mills to be "efficient, reliable, and economical" (Scott and Smith 1995; Nickull et al. 1991). A major advantage of fluidized bed systems is that they are less sensitive to changes in fuel condition (Tchobanoglous et al 1993, and Scott and Smith 1995), there is complete and efficient combustion, flexible operation, low emissions, and low operation costs (Meckel et al. 1990).

A benefit of burning sludge is steam generation, however, although there is a net steam production, it is low compared to the burning of bark or fossil fuels. Nonetheless, the burning of sludge can be used to offset some of the fossil fuel consumption of pulp and paper mills (Kraft and Orender 1991). Other benefits of incineration include a volume reduction of sludge cake up to 96 percent, the thermal destruction of toxic organic constituents as well as energy recovery (Vesilind and Ramsey 1996). The key elements in making sludge difficult to burn are high moisture contents, high ash contents and low oxygen contents (Kraft and Orender 1991).

3.2.5 ENERGY FROM BIOSOLIDS STUDIES

Sludges have been burned in conventional power boilers in North America for years, however, there are problems that occur with the increased burning of sludge. Such problems include: a reduction in boiler steam capacity unless sludge is kept to a low percentage of fuel input or dewatered to a great degree; increased maintenance due to grate blockages caused by sludge ash, and; an increased use of auxiliary fuel such as oil or gas to prevent boiler blackouts due to inconsistency of waste fuel moisture content.

Therefore, fluidized bed boiler systems are being implemented at an increasing rate. Fluidized bed sludge units have been operated throughout Europe, especially in Finland for approximately 10 years. Over 20 such installations are now running in Europe and the United States. Several of these systems are conversions of traditional travelling or sloping grate hog boilers that have been successfully converted to the fluidized bed type. Depending on the moisture of the sludge, properly-designed fluidized bed boiler systems can permit sludge feed input ratios of 50% or greater. Sludge drying technique and boiler configuration improvements are making sludge more of an asset than a liability for heat production (Pickell and Wunderlich 1995).

As mentioned, throughout the world, several fluidized bed combustion systems are being used for solid waste combustion. One of the first installations was in Lausanne, Switzerland. A small (150-ton/d) fluidized bed unit is used to co-dispose of municipal solid waste with dewatered wastewater treatment plant sludge. Steam is generated using a waste heat boiler, which is used for heating and electricity generation (Tchobanoglous et al. 1993). In Fujisawa, Japan, a 390-ton/d fluidized bed combustion system is used which employs a moving-bed design, allowing mass firing of unprocessed municipal solid waste. As well, a 700-ton/d plant in Duluth, Minnesota is used to co-dispose of 400 ton/d of municipal solid waste and 300 ton/d of dewatered wastewater treatment plant sludge (Tchobanoglous et al. 1993).

Fluidized bed combustion technology was used by a Spokane, Washington, newsprint manufacturer to burn its solid wastes and generate the hot water needed for a new paper recycling and de-inking facility. The volume of disposed solids was also reduced at the same time. The net heating value of paper mill solids can offset a significant percentage

of a mill's fuel cost, depending on the moisture and ash content of the sludge. Air emissions may also be reduced if a mill uses wasted solids as a fuel source instead of coal, due to the high sulfur content of coal. The primary and de-inked solids at the Spokane mill are dewatered to a solids content of about 43 percent (Moisture content = 57%) in a screw press. With fuels such as paper mill solids, and particularly mixed fuel streams, the thermal stability of fluidized bed systems helps to balance the combustion of the material and maintain the uniformity of combustion, both in temperature and gas concentration (Meckel 1993).

The University of Wisconsin-Stevens Point (UWSP) investigated three alternative technologies for a waste-to-energy project with the University as the primary consumer. Technologies explored included mass incineration, refuse derived fuel and pyrolysis. Mass incineration has been the most widespread technology but is not the most environmentally sound. The process requires burning waste without any preliminary processing. The refuse derived fuel involved pre-processing the waste to produce a uniform fuel, and the pyrolysis process is still considered experimental technology. The study concluded that the best alternative would be a refuse derived fuel fluidized bed boiler system. Such a system would have an environmental advantage over other incinerators because of the high heat transfer rates between the bed medium and the incoming fuel. The fluidized bed process would also allow for lower costs and a greater acceptance to varying types of fuel (Abubakr and Benjamin 1990).

In the United states, only one full-scale municipal solid waste pyrolysis system was ever built. The operation was constructed in El Cajon, California. The operation employed the Occidental Flash Pyrolysis System and did not achieve its primary goal to produce a

saleable pyrolysis oil. As a result the plant shut down after two short years of operation (Tchobanoglous et al. 1993).

The costs of energy are a critical factor in the economics associated with drying sludge. Clayton county, Georgia, developed the concept that pellets from the Clayton sludges could retain sufficient heat value to dry new sludge. The dried sludge possessed a heating value of 7500 Btu/lb. The county installed a two stage incinerator with could combust the pellets and then burn the hot gases to control potential emissions. Hot gases from the incinerator were then drawn directly into the triple pass dryer. This allowed a volume reduction prior to disposal. Burning the pellets enabled the County to realize an 80 -90 percent reduction in fuel costs compared to the operation of the system solely on natural gas. The success which Clayton county has enjoyed with the combustion of sludge pellets as a fuel source has resulted in a hiatus and renewed interest in such applications (Pepperman 1991).

"Incineration and the production of steam with sludge will continue to be an option for the foreseeable future" (Pickell and Wunderlich 1995).

3.3   COMPOSTING

Composting is a biological process of stabilizing organic matter under controlled conditions into a product that is rich in humus and provides organic matter and nutrients to the soil. Composting converts organic waste into useful products, thereby diverting them from disposal in landfills or combustion facilities (USEPA 1993). Compost derived from paper mill sludges can be used on agriculture, horticulture, forestry, and land reclamation (Sesay et al. 1997).

Data on solid residuals from the Canadian pulp and paper industry were derived from two recent surveys. The first survey was conducted in December 1994, and was answered by 93 mills (85% of the total pulp and paper mills in Canada). The second survey was conducted in January 1996, requested information for 1995, and was answered by 55 mills (52% of the total pulp and paper mills in Canada). The data from these surveys were averaged and extrapolated to the entire Canadian pulp and paper industry. Approximately one fifth of the solid waste reported for the whole country is generated from pulp and paper mills (Figure 3-6). This constitutes 6.4 million tons per year. This contribution also makes up half of the total reported for the Institutional, Commercial and Industrial (IC&I) sector. The amount of organic wastes reported from the IC&I sector is actually less than the amount of organic residues generated by the pulp and paper industry. Some or all of these residues from this industry were not counted in both studies. However, the amount of residues that take up space in landfills is of more concern than the total. The pulp and paper industry accounts for 64% of the total organic solid residues that is landfilled in the IC&I sector and 22% of the Canadian total (Figure 3-7). The 1.4 million tonnes of organic residues currently being landfilled by pulp and paper mills are a significant amount of raw material for the Canadian composting industry. (Reid and O'Connor 1996; Reid 1998).

Figure 3-6: Comparison of Pulp & Paper Mill Residues to Canadian and IC&I Totals (Reid and O'Connor 1996).

Total Solid Residues

Pulp & Paper — 6.4 (Total), 5.1 (Organics)
Canada — 33.2 (Total), 7.7 (Organics)
IC&I — 12.7 (Total), 2.4 (Organics)

X-axis: Million t/yr (0, 10, 20, 30, 40)

Legend: ■ Total, □ Organics
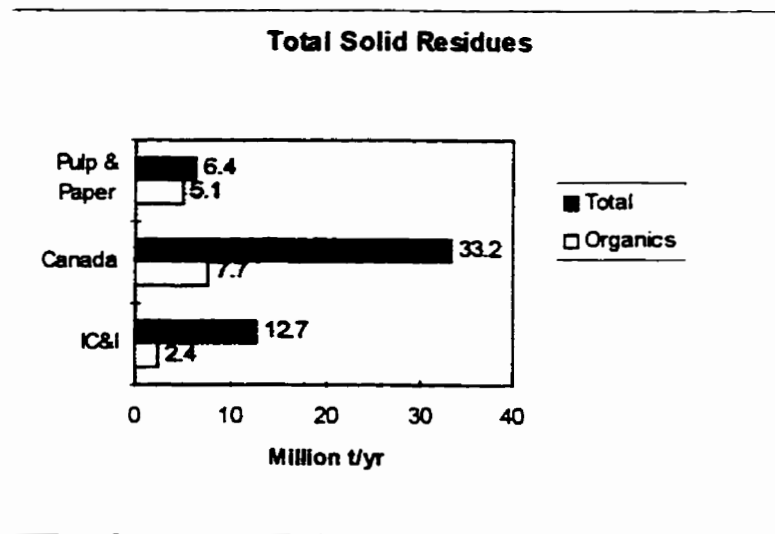
Figure 3-7: Comparison of Pulp & Paper Mill Landfilled Residues to Canadian and IC&I Landfilled Totals (Reid and O'Connor 1996).

Landfilled Solid Residues

Pulp & Paper — 2.4 (Total), 1.4 (Organics)
Canada — 22.1 (Total), 6.5 (Organics)
IC&I — 8.8 (Total), 2.2 (Organics)

X-axis: Million t/yr (0, 10, 20, 30)

Legend: ■ Total, □ Organics
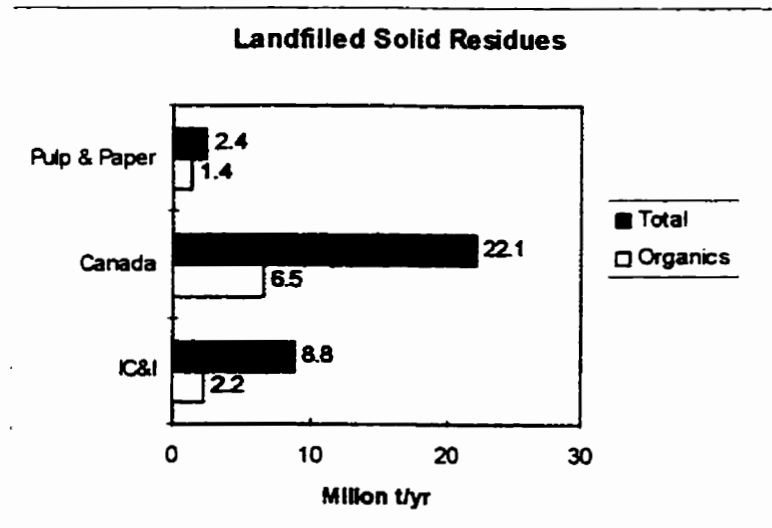
Primary and deinking sludges decomposability is largely influenced by the type of mill. Chemical pulp and fine paper mills, and mills that are recycling fine papers produce sludge that is nearly pure carbohydrate, these sludges are easily decomposed during composting. Mechanical pulp mills, newsprint mills, or mills recycling old newspapers produce sludge that is lignified and is more resistant to decomposition through composting. Secondary (biological) sludges are readily biodegradable and generally compost well. The heavy metal content of the raw sludge is determinant in the quality of the finished compost. Pulp and paper mill sludge has low heavy metal contents and generally do not exceed the AA (highest) standard set out by the Bureau de Normalisation du Québec. Furthermore, pulp and paper sludges do not contain detectable amounts of such organic contaminants as polychlorinated biphynols (PCB's), polyaromatic hydrocarbons (PAH's), or aromatic solvents (BTX) (Reid and O'Connor 1996).

In 1995, only 4% (100,000 tonnes) of pulp and paper solid residuals that were compostable were composted. Two-thirds of these compostable residues were landfilled and one-quarter was incinerated (Reid and O'Connor 1996).

3.3.1 COMPOSTING PROCESSES

Compost is the result of the composting process through which a humus-like material is produced that can be used as a soil conditioner. Composting can also be used to reduce the volume and weight of the waste material. Composting can either be carried out as aerobic or anaerobic. The principal difference is that the aerobic process requires oxygen to complete the conversion reactions while anaerobic processes must be oxygen free.

Aerobic composting is the most common of the two practices and will be discussed further. In the composting process, the organic fraction of wastes undergoes biological decomposition. The rate of decomposition is dependant on several parameters which include the nature of the waste, the moisture content, available nutrients as well as other environmental factors (Tchobanoglous et al. 1993). Papermill sludge normally has a moderate to high carbon:nitrogen (C:N) ratio, which often requires supplemental nitrogen (N) to facilitate complete composting. Compost is the finished resistant organic matter that remains after decomposition is complete. The following equation can be used to represent composting under aerobic conditions:

$$\text{organic matter} + O_2 + \text{nutrients} \rightarrow \text{new cells} + \text{compost} + CO_2 + H_2O + NH_3 + SO_4^{-2} + \text{heat} \quad [3\text{-}7]$$

The most common types of composting techniques include windrow composting, aerated static pile composting and in-vessel composting. Windrow composting consists of composting material in elongated rows that are typically 6 to 10 feet high by 14 to 25 feet wide at the base. The windrows are aerated through turning, which is usually accomplished by a front end loader or some type of turning equipment. Depending on the frequency of turning, complete composting can be accomplished in as little as three to four weeks or as much as three to five years as the organic carbon is transformed to stable humic compounds (Tchobanoglous et al. 1993; Campbell et al. 1991). After the turning period, the compost is allowed to cure for an additional three to four weeks. The aerated static pile composting process consists of a grid of aeration/exhaust piping which lies beneath the composting material. Typical heights of the piles are approximately 7 to 8 feet. Air is delivered to the pile through the grid of piping to provide the oxygen needed

for conversion reactions to occur. Therefore, no turning is required. Composting is usually complete in three to four weeks and cured for an additional three to four weeks. The in-vessel composting system is a process that is carried out in an enclosed vessel. Many shapes, sizes and types of such vessels exist. In-vessel composters are designed to minimize odours and process time by controlling environmental conditions such as temperature. The detention time varies from 1 to 2 weeks, but nearly all systems employ a 4 to 12 week curing period after the active composting period. Issues for implementing composting facilities include: the production of odours; the presence of pathogens; the presence of heavy metals, and; the definition of what constitutes a suitable compost. There are several design and operational considerations associated with aerobic composting as illustrated in Table 3-4 (Tchobanoglous et al. 1993).

The selection of a composting technology is based on capital and operating costs, land availability, operational complexity, and potential for nuisance problems (Table 3-5). The composting operation can be operated "in-house" by the waste producer or on a full-service contract where the composting facility is owned and operated by a vendor or third party (Tchobanoglous et al. 1993).

Table 3-4:   Aerobic Composting Design And Operational Considerations (Tchobanoglous et al. 1993).

Item	Comment
Particle Size	For optimum results, particle size should be between 25 and 75 mm.
Carbon:Nitrogen (C:N) ratio	Initial C:N ratios (by mass) should be between 20 and 30 for optimum results.
Blending and Seeding	Partially decomposed waste can be used to seed compost at 1 to 5 percent by weight to reduce composting time.
Moisture Content	Optimum range = 50 to 60 percent.
Mixing/Turning	Mix or turn on a regular schedule or as needed to prevent drying, caking and air channeling.
Temperature	Optimum temperature = 50 to 55°C for the first few days and between 55 and 60°C for the remainder of the active composting period.
Control of Pathogens	Temperature must be maintained between 60 and 70°C for 24 hours.
Air Requirements	Calculate the theoretical quantity of oxygen required.
pH Control	Optimum pH range is between 7 and 7.5. pH should not exceed 8.5 to minimize the loss of nitrogen.
Degree of Decomposition	Degree of decomposition can be estimated by measuring the final drop in temperature, degree of self heating capacity, amount of decomposable and resistant organic matter in the composted material, rise in the redox potential, oxygen uptake, growth of the fungus *Chaetomium gracilis*, and the starch-iodine test.
Land Requirement	Land requirements for a plant with a 50 ton/d capacity will be 1.5 to 2.0 acres.

Table 3-5: Comparison of Composting Processes (Tchobanoglous et al. 1993).

Item	Windrow	Aerated Static Pile	In-Vessel (completely mixed)	In-Vessel (plug flow)
Capital costs	Generally low	Generally low in small systems, can become high in large systems	Generally high	Generally high
Operating costs	Generally low	High (in sludge systems where bulking agents are used)	Generally low	Generally low
Land requirements	High	High	Low, but can increase if windrow drying or curing required	Low, but can increase if windrow drying or curing required
Control of odours	Depends on feedstock, potential large-area source	May be large-area source but can be controlled	Potentially good	Potentially good
Potential operating problems	Susceptible to adverse weather	Control of airflow rate is critical	High operational flexibility, system may be mechanically complex	System may be mechanically complex

3.3.2 COMPOSTING MARKETS

Composting is encompassed as a form of recycling, where recycling, along with waste prevention, combustion and landfill disposal, is a key component of an integrated solid waste management strategy. A material is only considered recycled when all steps, including collection, separation, processing, remanufacture and marketing are completed. Therefore, understanding the markets for composting is key to continued and expanded recycling. Like all markets, the markets for compost are influenced by the laws of supply and demand. Governments support recycling by promoting the purchase of recycled materials; providing assistance to recycling organizations; and researching, developing, and evaluating policy options (USEPA 1993).

The supply of compost can be influenced by several factors such as landfill and combustor capacity pressures and high disposal fees. Many landfills have also banned certain materials for disposal. Also, certain materials are not desirable for combustion due to high moisture contents, which inhibits the complete burning of the material and results in little net useable energy for power or steam generation. Air emissions are another major concern with the combustion of waste material. Suppliers should identify markets before initiating composting operations and adjust compost production accordingly to ensure the proper supply. Failure to identify and understand potential markets for compost can result in over- or under-production. However, since existing facilities have not been operating long enough to make accurate forecasts, the long-term supply of compost is uncertain (USEPA 1993).

There are five major market segments for compost, these include: agriculture; landscapers (industrial, commercial, golf courses, cemeteries, athletic fields, landfill

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covers, damaged soils, etc.); nurseries (plant crops, forest seedling crops, reforestation, etc.); public agencies (highway median strips, parks, recreational areas, etc.); and residents (home landscaping, home gardening, etc.). Different grades of compost are required for the different market segments. The most important factors affecting the demand for compost are compost quality and consistency. High quality, mature compost should not contain foreign matter, and should have a dark colour, uniform texture, and a pleasant earthy odour. It should also contain minimal levels of chemical residues and heavy metals, have a high concentration of organic matter, contain nutrients and be free from pathogenic organisms. However, uniform specifications have not been developed for compost, therefore there is often skepticism in some potential compost users, for example the agricultural community. Potential users may also be steered away due to the fact that standard laboratory procedures have not been established. Complementary products also affect the marketability of compost. Complementary products include fill dirt, top-soils, riverbottom silt, potting soils, custom soil mixes, bark mulch and wood chips, manure, peat moss, mushroom compost, perlite, and vermiculite. Many of these products have a long history of consistency, availability, reliability, acceptance and use in agriculture, horticulture, public and private landscaping projects, and residential gardening. Another factor affecting the demand for compost is distance. Shipping costs should not exceed the value of the compost, although, various strategies can be employed to mitigate high transportation costs. For example, local markets can be developed for compost, backhauling compost in cleaned otherwise empty departing trucks, establishing a network of distribution centers that each maintain an adequate inventory, and locating composting facilities near the primary compost users' sites. The largest potential market

for compost is the agricultural industry. Agriculture is also the most difficult market to penetrate since compost must be available at the appropriate times of the year, contain low levels of potentially toxic substances, be offered at low cost and be accepted by farmers. Landscapers are potentially large users of compost but have expressed concern that compost may contain harmful amounts of viable seeds, herbicides and pesticides. The nursery industry use of compost is related to the economy of the housing industry. As home sales rise, the demand for nursery products rise as well. Public agencies have the potential to use large amounts of high- and low-quality compost. The amount of compost the residential segment will use depends on the ability of the suppliers to consistently produce a quality product at a reasonable cost (USEPA 1993).

Factors that influence compost markets include: professional support; perception; environmentalism; community responsibility; research and development; consumer acceptance; geographic area (seasonal); demography; market accessibility; regulatory/quality/standards; local soils; cost of waste disposal; political will-recycling, and; cost (Chase 1996). Marketing compost use summaries for Canada (1995) and the United States (1992) are illustrated in Tables 3-6 and 3-7 respectively.

Table 3-6: Marketing Compost Use Summary - Canada (1995 data) (Chase 1996).

Application	Actual Use (Million Yd^3)
Bagged/Retail	0.2
Landscapers Delivered Topsoil	0.6 - 0.7
Municipal Landfill Cover/Give-away	0.4
Mine Reclamation/Bioremediation	0.1
Total	1.4*

*11% of potential supply
Potential demand = 13

Table 3-7: Marketing Compost Demand/Use Summary - USA (1992 data) (Chase 1996).

Application	Potential Demand (Million Yd^3)	Penetration (%)	Actual Use (Million Yd^3)
Bagged/Retail	8.0	80	6.5
Landscapers	2.0	<20	0.4
Delivered Topsoil	3.7	<5	0.2
Landfill Cover	0.6	<5	?
Mine Reclamation	0.2	<5	?
Nurseries -Container	0.9	<50	0.5
-Field	4.0	<1	?
Sod	20	<1	0.2
Siviculture	104	<1	1.0
Agriculture	895	<1	8.0
Sub Total			17
Other			7
Total	1038.4	<2	24*

17% of potential supply
Potential demand = 140

Compost must be of a consistent size, free from contaminants and metals, and free from objectionable odour to be marketable. The specific use of the compost will govern the type of processing used to prepare the compost for marketing. For example, additives may be added to enhance the value of the final product (Tchobanoglous et al. 1993).

3.3.3 BENEFITS/DRAWBACKS OF COMPOSTING

Paper mill sludge has a high C:N ratio and excessive or uncontrolled application can impair plant growth due to nitrogen immobilization. However, composting paper mill sludges prior to land application could: reduce sludge mass and volume, thus decreasing transportation costs; improve the C:N ratio therefore reducing nitrogen immobilization problems and allowing higher rates of application; minimize odours; biodegrade compounds that are toxic or inhibitory to plant growth, including possibly chlorinated

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organics; increase humic components and cation exchange capacity, improving nutrient retention and availability, and produce a higher value product suitable for horticultural and agricultural applications (Sesay et al. 1997; Campbell et al. 1991).

Since the 1970's, numerous attempts at composting pulp and paper mill sludge have been undertaken, however few have been successful in producing a material suitable for agricultural and horticultural use. This can be attributed to the fact that the composition of pulp and paper mill sludges differ from one mill to the next and therefore composting methods developed for one mill may be unsuitable for another (Jackson and Line 1997). Although composting has been examined, it has not yet gained a lot of support. The process can require a considerable capital investment for equipment and buildings and odour can be a problem. Also, production costs can be as high as $30/t (1995 U.S. currency), and the market for compost is limited (Pickell and Wunderlich 1995).

Pulp and paper companies are often reluctant to enter into composting ventures since they generally prefer to concentrate on making paper, and not involve themselves in unfamiliar processes and markets for utilizing their residues. Consequently, it is often more common that the composting operation remains a separate business than the mill. Mills are also often insecure about distributing their residues to maintain their environmental image and avoid negative publicity. Cost is also always an important consideration (Reid and O'Connor 1996).

"A successful composting operation is highly dependent on proper operation and maintenance as well as design" (Tchobanoglous et al. 1993). Research is needed to evaluate process variables and physical and chemical changes in compost (Campbell et al. 1991).

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3.3.4 COMPOSTING STUDIES

The feasibility of paper sludge composting has been demonstrated through several laboratory, pilot and field scale studies (Sesay et al. 1997). The first Canadian community to use in-vessel composting for biosolids management was the City of Guelph, Ontario. Guelph was disposing its dewatered biosolids (18% solids) at the city's landfill, the composting facility was constructed to divert these biosolids from the landfill and resolve handling and odour problems. A system with a design capacity of 18.5 dry metric tons/day was selected to operate for five days per week. The total cost of the facility was approximately $16 million (1995 Canadian currency) with annual operating costs estimated at approximately $160 (Canadian) per dry metric ton of biosolids processed. The facility began operating in November 1994. Guelph expects to use the compost as lift cover or top dressing at its landfill, for restricted application on agricultural lands, and landscaping. Additional markets are possible depending on the success of ongoing efforts to decrease metal concentrations at the source thereby improving compost quality (Gies 1995).

Each year, 700,000 tonnes of sludge (approximately 40% solids on average) is produced by the United Kingdom paper industry. The industry is searching for alternatives to landfilling due to tighter environmental regulations and increasing tipping fees. The combustion of sludge in the UK is not very widespread, this is mainly attributed to its high capital and running costs. High moisture contents require expensive drying and high ash contents may cause furnace fouling, large amounts of ash would also still have to be disposed of. Therefore the feasibility of composting paper pulp sludge using an aerated static pile was examined. This method was chosen as it allows a high degree of process

control at fast rates of decomposition, while remaining relatively inexpensive. The study involved composting paper sludge from the Bridgewater Paper Company in the UK. Results indicate that the primary, secondary, and deinking sludges, in combination were successfully composted using the aerated static pile method. In two weeks, most of the organic matter was stabilized and more than 30 percent of the initial volatile solids content was decomposed. The respiration rate dropped more than 80 percent to 0.8 mg O_2/g VS/hr during that time. A further four to five weeks of non-aerated curing could also improve the quality of the compost with respect to phytotoxicity. Only a small volume reduction was observed, however, a large weight reduction occurred, mainly due to water evaporation (Sesay et al. 1997).

Approximately 50,000 tonnes of pulp and paper mill sludge is produced per year at Australian Newsprint Mills, a pulp and paper mill located in Southern Tasmania. All of the sludge produced at this mill is currently landfilled. Composting studies are being investigated because the landfill is near full capacity and several million dollars will be required to construct a new landfill site complying with statutory guidelines. When considering composting a pulp and paper mill sludge with a high C:N ratio in large-scale windrows that are periodically turned, the two major control variables are nutrient and temperature management. Nutrient content and temperature have a significant affect on microbial activity which govern the rate of decomposition of the substrate. Temperature may be controlled by regulating heat loss while nutrient content may be manipulated by nutrient addition. If excess loading of nutrients in paper mill sludge occurs at the start of composting, the risk of nutrient loss to leaching and subsequent ground water pollution may result. Therefore nutrient loadings should match immediate microbial requirements

and prevent the possibility of ground water pollution during composting. The study examined the relationship between nutrient addition and temperature during composting of paper mill sludge using small-scale reactors. The initial chemical composition of the waste indicated that N, P and K quantities were low and would have to be added to obtain a suitable ratio for composting. The highly fiberous paper mill sludge was nutrient poor and had no heavy metal contamination. Results indicate that when compared to composting at 55°C, composting at 35°C resulted in a slower rate of CO_2 formation and an extended period of O_2 consumption. The rate of O_2 consumption is therefore positively correlated with temperature, this is also similarly reported by Jeris and Regan (1973). Not only did composting occur at a faster rate at the higher temperature, but a delay of 30-50 days occurred in maturation was observed at 35°C. No effects were observed on respiratory activities or rate of decomposition with respect to the method of nutrient addition, however, there was a major influence on pH which determined the intensity and period of ammonia volatilization. In terms of nitrogen conservation, the addition of nutrients in an incremental manner was found to have no benefit without pH management. However, incremental nutrient addition with pH management is expected to result in a finished compost with a C:N ratio adequate for soil application, given the potential for leaching of nutrients in excess of immediate requirements in large-scale windrows (Jackson and Line 1997).

CHAPTER 4

SAMPLING AND ANALYSIS FOR UTILIZATION ALTERNATIVES

Sampling of Pine Falls Paper Company's solid waste is a crucial step in the determination of the physical and chemical properties of the biosolids produced at the PFPC. A sound sampling plan ensures that representative samples of the waste are collected over a sufficient period of time to represent the variability of the waste. This chapter therefore investigates and describes the expected biosolids characteristics at PFPC, the sampling theory, procedures for simple random sampling, preliminary statistical considerations, and methods for sampling and analysis. Proper characterization of the PFPC biosolids can be used to estimate environmental impacts and to complete conceptual designs for alternative biosolids utilization techniques such as energy-from-waste, land application, and composting. The data could also be scientifically defendable in any environmental assessment process, such as environmental impact statements or Clean Environment Commission hearings.

4.1   PFPC EXPECTED BIOSOLIDS CHARACTERISTICS

PFPC produces 200 plus tonnes of biosolids per day from their effluent treatment and deinking plants at a moisture content of approximately 67 percent (Sopuck 1997) and a sludge composition ratio of 40, 21, and 39 percent for primary, secondary, and deink sludge respectively (Haigh 1997). Table 4-1 is a list of sludge characteristics from QUNO Corporation where the nature of the sludge is expected to be similar to that of the sludges produced at PFPC (Poetker MacLaren 1995).

Table 4-1: QUNO Sludge Characteristics (Poetker MacLaren 1995).

Parameter	Concentration (mg/kg dry weight basis unless otherwise noted)
Dry Solids (%)	38.39
Volatile Solids (%)	69.16
Total Kjeldahl Nitrogen	9880
Ammonia Nitrogen	344
Nitrate Nitrogen	9.60
Nitrite Nitrogen	<1
Chloride	108
Sulfate	913
Total Phosphorus	1510
pH	7.81
Phenolic Compounds, as Phenols	0.144
Total Calcium	17800
Soluble Calcium	950
Total Magnesium	1370
Soluble Magnesium	130
Total Sodium	1030
Soluble Sodium	890
Cobalt	<1
Zinc	150
Cadmium	<0.5
Boron	<2
Copper	260
Molybdenum	3.9
Lead	12
Nickel	10
Chromium	12
Potassium	750

Table 4-2 illustrates the results of data analysis performed on the PFPC biosolids data by the University of Manitoba's Soil Science Department. The data used to derive the mean element concentrations are the result of analysis performed on PFPC biosolids which were sampled during May, June, July, and August of 1996.

Table 4-2: PFPC Biosolids Elemental Composition (Fuller 1997).

Element	Mean Element Concentration in Biosolids (mg/kg)
N	20000 - 50000
P	5000-10000 (mean avg. = 6700)
Cd	1.7
Cr	13.7
Co	0.9
Cu	14.2
Pb	3.9
Ni	6.9
Zn	75

In general, paper mill sludge tends to be highly fibrous, while often deinking mill sludge has high ash levels, depending on the type of recycled paper used (Scott and Smith 1995). Table 4-3 illustrates that not only do mills produce varying amounts of sludge, but the sludges produced are distinctly different in composition.

Table 4-3: Analysis of Sludge Produced from Different Sources (Bark and Wastepaper Values included for Comparison) (Scott and Smith 1995).

Source	Analysis (%)							Heating Value (MJ/kg)
	Solids	Ash	C	H	S	O	N	
Bleached pulp mill	33.4	1.9	48.7	6.6	0.2	42.4	0.2	20.1
Pulp mill	42.0	4.9	51.6	5.7	0.9	29.3	0.9	21.5
Kraft Mill	37.6	7.1	55.2	6.4	1.0	26.0	4.4	24.1
Kraft Mill	40.0	8.0	48.0	5.7	0.8	36.3	1.2	19.8
Deinking mill	42.0	20.2	28.8	3.5	0.2	18.8	0.5	12.0
Deinking mill	42.0	14.0	31.1	4.4	0.2	30.1	0.9	12.2
Recycle mill	45.0	3.0	48.4	6.6	0.2	41.3	0.5	20.8
Recycled paper mill	50.5	2.8	48.6	6.4	0.3	41.6	0.4	20.6
Bark	54.0	3.5	48.0	6.0	0.1	42.1	0.3	20.3
Bark	50.0	0.4	50.3	6.2	0.0	43.1	0.0	20.8
Wood chips	79.5	0.2	49.2	6.7	0.2	43.6	0.1	19.4
Wastepaper	92.0	7.0	48.7	7.0	0.1	37.1	0.1	25.0

4.2 SAMPLING THEORY

The initial and perhaps most critical element in a program designed to evaluate the physical and chemical properties of a solid waste is the plan for sampling the waste. Once the scientific objectives have been clearly identified, a suitable sampling strategy, predicated upon fundamental statistical concepts, can be developed.

A sound sampling plan requires that representative samples of waste be collected which exhibit average properties of the whole waste, and enough samples be collected over a period of time sufficient to represent the variability of the waste. These two factors are responsible for ensuring the sampling accuracy. If measurements are sufficiently

accurate and precise, they will be considered reliable estimates of the properties of the waste. For the purpose of evaluating solid waste, the confidence level for all practical purposes is 90%. Sampling accuracy is usually achieved by some form of random sampling and by taking an appropriate number of samples from the population. Maximizing the physical size of the samples also increases sampling accuracy (American Chemical Society 1992 & USEPA 1986).

Simple random sampling can be used if the following assumptions are made: 1) The waste is heterogeneous with regard to its chemical characteristics and random heterogeneity remains constant from batch to batch; and 2) The validity of a confidence interval for the true mean concentration of a chemical property of a solid waste is based on the assumption that individual concentrations of the property exhibit a normal distribution. Simple random sampling is used so that every part of a waste has a theoretically equal chance of being sampled, when there are no known distinct strata in a waste over space or time (USEPA 1986).

4.3 SIMPLE RANDOM SAMPLING GENERAL PROCEDURES

1) Obtain preliminary estimates of the sample mean (x) and sample variance (s^2) for each property of solid waste that is of concern.

$$x = \frac{\sum x_i}{n} \qquad\qquad [4\text{-}1]$$

$$s^2 = \frac{\sum x^2 - (\sum x_i)^{2/n}}{n-1} \qquad\qquad [4\text{-}2]$$

2) Estimate the appropriate number of samples (n) to be collected from the waste.

$$n = \frac{t^2 \times s^2}{\Delta^2}$$ [4-3]

Where Δ is the variability in the mean, and t is the value obtained from a T table for a particular confidence limit.
Determine n values for each property of concern and select the greatest value.

3) Randomly collect at least n samples from the waste. Collect a few extra samples to provide protection against poor preliminary estimates of x and s^2. Be sure the size of samples collected are maximized.

4) Analyze the samples for each property of concern. Superficially (graphically) examine each set of analytical data for obvious departures from normality.

5) Calculate the sample mean (x), sample variance (s^2), standard deviation (s), and standard error (s_x) for each set of analytical data.

$$x = \frac{\sum x_i}{n}$$ [4-4]

$$s^2 = \frac{\sum x^2 - (\sum x_i)^{2n}}{n-1}$$ [4-5]

$$s = \sqrt{s^2}$$ [4-6]

$$s_x = \frac{s}{\sqrt{n}}$$ [4-7]

7) Determine the variability from the mean (Δ) for the particular confidence limit chosen.

$$\Delta = \sqrt{\frac{t^2 \times s^2}{n}}$$ [4-8]

8) For further iterations determine number of samples required (n), using the newly calculated values of x and s^2.

(USEPA 1986)

4.4 PRELIMINARY STATISTICAL CONSIDERATIONS

Section 4.3 identified the general procedures for simple random sampling, where the first step is to obtain preliminary estimates of the sample mean (x) and sample variance (s^2) for each property of solid waste that is of concern. These preliminary statistical analyses lay the groundwork for further sampling and analysis. Existing data was provided by PFPC for past analysis performed on their biosolids. Data provided included over one full year's worth of solids data, as well as results of periodic analyses on various biosolids properties. The samples for these periodic analyses were collected as grab samples on the dates indicated in Table 4-4, the ratios of primary, secondary, and deinking sludge are also illustrated in this table. It is important to note that most of the data obtained was sampled and analysed prior to the deinking plant coming on line. The results of the preliminary estimates of x and s^2 are illustrated in table 4-5, the raw data is contained in appendix A.

Table 4-4: Primary/Secondary/Deink Ratios on Preliminary Sampling Dates.

Date	% Primary Sludge	% Secondary Sludge	% Deinking Sludge
May-10	55.5	44.5	
May-24	36.6	63.4	
May-27	32.1	67.9	
June-06	60.9	39.1	
July-04	37.5	62.5	
July-09	57.4	42.6	
July-11	49.4	50.6	
July-16	51.9	48.1	
July-18	68.4	31.6	
July-29	34.3	61.5	4.2
Nov-14	23.8	49.2	27

Table 4-5: Preliminary Values For x, s^2, s, and s_x.

Property	n	x	s^2	s	s_x
Solids (%)	765	28.01	15.10	3.89	0.14
Organic Matter (%)	10	90.10	50.22	7.09	2.24
C:N Ratio (%)	10	18.28	14.02	3.74	1.18
Total Organic Carbon (%)	11	50.76	16.33	4.04	1.22
Total Kjeldahl Nitrogen (%)	10	3.15	0.68	0.83	0.26
Ammonia (ug/gm)	6	870.33	187945	434	177
Nitrate (ug/gm)	7	2.64	18.89	4.35	1.64
Trace Elements (ug/gm)					
Aluminium	10	1934	349582	591	187
Antinomy	9	0.96	0.72	0.85	0.28
Arsenic	10	0.50	0.11	0.33	0.10
Barium	10	81.77	637.55	25.25	7.98
Beryllium	10	0.22	0.07	0.27	0.09
Bismuth	9	0.48	0.03	0.17	0.06
Cadmium	10	1.68	0.17	0.42	0.13
Calcium	9	11406	3723878	1930	643
Chromium	10	13.43	34.73	5.89	1.86
Cobalt	10	0.87	0.04	0.19	0.06
Copper	10	14.04	3.80	1.95	0.62
Iron	9	2050	277400	527	176
Lead	10	3.87	0.88	0.94	0.30
Magnesium	9	1430	260100	510	170
Molybdenum	10	1.59	0.08	0.29	0.09
Nickel	10	6.4	1.82	1.35	0.43
Phosphorus	9	6002	4108344	2027	676
Selenium	9	1.52	0.85	0.92	0.31
Silicon	9	321	52816	230	77
Silver	9	0.156	0.004	0.061	0.020
Strontium	10	16.92	14.30	3.78	1.20
Thallium	10	0.30	0.06	0.25	0.08
Tin	10	39.55	1685.57	41.06	12.98
Titanium	9	27.80	1154.30	33.97	11.32
Vanadium	10	8.07	3.26	1.81	0.57
Zinc	10	74.13	130.85	11.44	3.62

Note: Sampling dates and raw data in appendix A

Step two of the general procedures for random sampling (Chapter 4.3) dictate that the number of samples for further testing be estimated for each property of concern. The following physical and chemical properties have been selected: % solids, organic matter, total Kjeldahl nitrogen, total organic carbon, phosphorus and selenium. The % solids property was selected due to its abundant preliminary data as well as the fact that it is the only physical preliminary data obtained. Organic matter and total organic carbon is important for composting and land application purposes, as well as combustion technologies. Total Kjeldahl nitrogen and phosphorus were selected due to their nutrient value in composting and agriculture and the potential of nitrogen as a gaseous emission in combustion technologies. Also one trace element was chosen, the preliminary data for the trace elements (Table 4-5) was compared to category A of the CCME Guidelines for Compost Quality. The trace element which was closest to the category A guideline was selected (Selenium). Table 4-6 illustrates the comparison of the CCME Guidelines for Compost Quality category A with the preliminary average concentration in PFPC biosolids. Category A was selected as it defines "compost that can be used in any application, such as agricultural lands, residential gardens, horticulture operations, the nursery industry, and other businesses" (CCME 1996). Table 4-5 illustrates that certain properties/elements within PFPC's had a high variability relative to the others. Elements with high concentration tended to have a greater degree of variability as would be expected.

Table 4-6: Comparison of CCME Guidelines for Compost Quality Category A and PFPC Biosolids Concentration.

Trace Elements	CCME Category A[A] Maximum Concentration within Product (mg/kg dry weight)	Average Concentration in PFPC Biosolids (mg/kg)[B]	% Difference Between CCME Category A & PFPC Biosolids
Arsenic (As)	13	0.5	96.2
Cadmium (Cd)	3	1.68	44.0
Cobalt (Co)	34	0.87	97.4
Chromium (Cr)	210	13.43	93.6
Copper (Cu)	100	14.04	86.0
Mercury (Hg)	0.8	No Data[C]	No Data[C]
Molybdenum (Mo)	5	1.59	68.2
Nickel (Ni)	62	6.40	89.7
Lead (Pb)	150	3.87	97.4
Selenium (Se)	2	1.52	24.0
Zinc (Zn)	500	74.13	85.2

A -- Category A compost can be used in any application (CCME 1996)

B -- Average PFPC biosolids concentrations extracted from table 4.3.2

C -- No preliminary data available for this trace element

4.5   METHODS FOR SAMPLING AND ANALYSIS

4.5.1   STATISTICS

Simple random sampling is employed so that every part of the waste has a theoretically equal chance of being sampled. This method is the option of choice since there are no known distinct strata in the waste over time or space.

The confidence interval employed to evaluate solid waste is, for all practical purposes, a 90% interval. The number of samples required for analyses are dependent on the variability we are willing to accept in the mean. The following table (Table 4-7)

illustrates the number of samples required for a 90% confidence interval and varying degrees of variability in the mean (Δ) from a number of physical and chemical properties. The sampling plan outlined in this document has been confirmed to be statistically sound by a statistical advisor of the Statistics Department, University of Manitoba.

Table 4-7: Number of Samples Required (n)

Property	Δ=1%	Δ=5%	Δ=10%	Δ=15%	Δ=20%	Δ=25%	Δ=30%
% Solids	316	14	5	3	2		
Organic Matter	104	6	3	3	2		
Total Kjeldahl Nitrogen	1126	47	13	7	5	4	3
Total Organic Carbon	106	6	3	3	2		
Phosphorus	1862	77	20	10	6	5	4
Selenium	6047	242	62	28	16	11	8

where $n = t^2 * s^2 / \Delta^2$
where t=values obtained from a T table chosen for a particular confidence limit (90%)
where Δ=variability from the mean
where s^2 values derived from existing PFPC data (Appendix A)

Choosing a value of 10 samples to be further analyzed for energy-from-waste, composting and direct land application properties, will result in a 90% confidence interval so that the properties illustrated will be within 3 to 27% of the mean. I.e. 90% confident that our value will be within 3 to 27% of the population mean depending on the property of interest.

4.5.2 ANALYTICAL LABORATORIES

Energy-from-Waste

Geochemical Testing, a division of Energy Center, Inc., of Somerset PA, is an analytical laboratory which performs analysis of the characterization of the biosolids with respect to the energy-from-biosolids alternative. This analysis is largely based on emissions and energy content. Geochemical Testing performs the analysis required on a daily basis and uses the following ASTM test procedures:

- Moisture: Air Dry Loss   = D-3302
             Residual Moisture   = D-3173
- Ash   = D-3174
- Volatile Combustible Matter   = D-3175
- Fixed Carbon   = Calculation
- Sulfur   = D-4239
- Energy Content   = D-1989
- Ultimate Analysis (%C, N, O, H)   = D-5373
- Fusion Point of Ash   = D-1857

Geochemical Testing has quoted a price per sample of $119.65 (U.S. currency). Total analysis costs for 10 samples would therefore be $1196.50 (U.S. currency), or $1675.00 (Cdn. Currency). Additional costs include shipping of the samples to Somerset PA., as well as time spent for the person designated to collect the samples.

Composting/Land Application

Norwest Labs, of Winnipeg MB, performs analytical characterization of the biosolids with respect to land application and composting alternative. The required analysis and procedures are listed as follows:

- Heavy Metals→Al, Sb, As, Ba, Be, Bi, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, P, K, Se, Si, Ag, Na, Sr, Tl, Sn, Ti, V, Zn by EPA 3051 Nitric acid microwave digestion, plus Hg by cold vapour (Package TT9, method U.S. EPA 6019, and U.S. EPA 245.5 for Hg)

- Total Macronutrients→% Moisture, Total N (TKN), P, K, S, pH, Electrical Conductivity, Ca, Na, Mg, ammonium, organic nitrogen (Package MA2, method Leco, U.S. EPA 6010)
- Available Macronutrients→Available NH_4-N, NO_3-N, P, K, SO_4-S (Package F10)
- Micronutrients→zinc, copper, iron, manganese and boron (Package E, method U.S. EPA 6010)
- Chloride→ (Package FSCL, method APHA4500-Cl-:E)
- % Organic Matter & Total Organic Carbon (TCO)→ (Package CL41, method Mss 3.611, Leco)
- Solids→Total, plus Volatile and Fixed (Package CL43)
- Chlorophenols (Package PCP2, method EPA8040)
- EOX - extractable organic halides (Package EOX1, method CPP H.6P and EPA 1650)

Note that all samples should undergo ten analyses except for the hazardous organics (chlorophenols, extractable organic halides). These hazardous organics should be run in duplicate as a composite from the ten samples. These parameters are analyzed only to show that PFPC biosolids do not contain these organics. Also, redundancy of analysis exists as a useful tool in checking the precision within and between laboratories.

Norwest Labs has quoted a price for the outlined analysis at $3135.00. Additional costs include shipping of the samples, as well as time spent for the person designated to collect the samples.

4.5.3 SAMPLING PERIOD

In order to achieve samples representative of the population with maximum accuracy and realistic variability, sampling should be executed over a period of four weeks. This would require someone to collect the samples directly after the belt press dewatering process at times specified (random samples, therefore samples may be required day or night over a one week period). Training should be provided to treatment plant operators

for sampling, these samples would be collected, composited, and shipped for analysis. Samples should be collected avoiding transitory events. Start-up, shut-down, and maintenance transients can result in the generation of a waste that is not representative of the normal waste stream. If a sample was unknowingly collected at one of these intervals, incorrect conclusions could be drawn.

4.5.4 BUDGET

Research Stipend
    x (full research stipend) = $ 288.50/week
    y (current research stipend) = $ 173.00/week
    8 weeks * (x – y) = 8 weeks * $ 115.00/week   = $ 920.00

Transportation costs (U of M to PFPC round trip $\approx$ 200 km)
    200 km/trip * 30¢/km * 11 trips   = $ 660.00

Geochemical Testing analysis costs
    US$ 119.65/sample * 1.4 CAN$/US$ * 10 samples   = $ 1675.00

Norwest Labs analysis costs
    10 samples @ 255.75, and 2 samples @ 288.75   = $ 3135.00

Shipping costs
    Samples shipped to Norwest Labs and
    Geochemical Testing (estimated)   = $ 750.00

Miscellaneous costs (containers, etc.) (estimated)   = $ 350.00

Cost Estimate   = $ 7490.00

Contingency (5% of above)   = $ 375.00

TOTAL COST ESTIMATE   = $ 7865.00

CHAPTER 5

ENGINEERING CALCULATIONS

5.1 LAND APPLICATION

The soil science department at the University of Manitoba has been conducting land application studies of PFPC's biosolids in Barley production. The study began in 1997 to investigate the impact of pulp sludge application to agricultural lands by measuring the effects on crop nitrogen utilization, physiological effects on crop production, and metal loading in the grain harvested. Results indicated that there were no toxic effects on the emergence of barley plants. Plots of low nitrogen and high sludge inhibited plant growth, but control plot yields were surpassed by high sludge plots as nitrogen treatments increased. Also, the sludge appears to be an effective sponge for immobilizing nitrogen (Hicks and Fuller 1998). Table 5-1 illustrates the sludge characteristics as determined through this study. The study will continue through 1998 to repeat the sludge and nitrogen plot experiment and look at the decomposition rate of the sludge.

Table 5-1 PFPC Sludge Characteristics – Land Application Trials (Hicks and Fuller 1998).

Parameter	PFPC Biosolids
pH	7.3
EC	1.7
Nitrate-N (ug/g)	<1
Phosphate-P (ug/g)	>60
Potassium (ug/g)	405
Sulfur (ug/g)	>20
Organic Matter (%)	74-80
Ammonium (ug/g)	71
Total Nitrogen (%)	1.1
Total Phosphorus (%)	0.15
C:N Ratio	35-45:1
Moisture (%)	70
Arsenic (mg/kg)	1.9
Barium (mg/kg)	144
Cadmium (mg/kg)	0.14
Chromium (mg/kg)	9.9
Copper (mg/kg)	71
Lead (mg/kg)	5.0
Nickel (mg/kg)	3.9
Selenium (mg/kg)	2.3
Vanadium (mg/kg)	5.2
Zinc (mg/kg)	83

5.2 ENERGY FROM BIOSOLIDS

Preliminary engineering calculations have been made using data for a deinking mill sludge described in Table 4-3. This data was used to best represent expected result from the biosolids at the PFPC. Table 5-2 illustrates the result of these preliminary calculations, including estimations of the biosolids chemical composition, energy content, volume reduction and volume of residue after combustion, effects of excess air on temperature and composition of flue gases, and materials heat balance. Raw calculations

are included in appendix B. PFPC is currently planning burning trials to test the energy content and emissions by burning their biosolids in their boilers.

Table 5-2: Summary of Energy from Biosolids Preliminary Calculations.

Property	Value
Estimated Chemical Composition	$C_{415}H_{699}O_{302}N_{10}S$
Estimated Energy Content (Theoretical)	17.1 MJ/kg , 7332 Btu/lb
Estimated Energy Content (Measured, Tbl. 4-3)	12.2 MJ/kg , 5245 Btu/lb
Difference between Theoretical & Measured Energy Contents	29 %
Estimated Volume Reduction through Combustion	95%
Estimated Units of Air Required for Combustion per Unit of Biosolids	3.83
Estimated Temperature of Flue Gas at 50% Excess Air	1116 °C , 2040 °F
Estimated Temperature of Flue Gas at 100% Excess Air	896 °C , 1645 °F
Estimated Gross Heat Input for the Combustion of 200 tonnes/day of Biosolids	2.44E6 MJ/day , 2312.6 Btu/day
Estimated Total Heat Loses for the combustion of 200 tonnes/day of Biosolids	0.38E6 MJ/day , 364.6 Btu/day
Estimated Net Heat Available in Flue Gases for the Combustion of 200 tonnes/day of Biosolids	2.01E6 MJ/day , 1948.0 Btu/day
Estimated Combustion Efficiency	84.2%
Typical Boiler Efficiency	85%
Estimated Overall Combustion Efficiency	71.6%[A]

A – This value (Estimated Overall Combustion Efficiency) is consistent with values obtained in modern MSW combustion systems (Tchobanoglous et al 1993)

5.3 COMPOSTING

Using material feedstock characteristics, preliminary calculations have been made to determine volume of material to be composted, volume of material on composting pad, number of windrows required, composting area requirements, curing area requirements, compost storage area, and overall pad dimensions. Raw calculations are included in Appendix C, results are illustrated in Table 5-3. Laboratory experimentation concerning required nitrogen addition for composting was conducted on a bench-scale and is examined in the subsequent chapters of this report.

Table 5-3: Composting Area Requirements.

Parameter	Value
Volume of Mixture at Start-Up (m^3/year)	346500
Material Volume of Composting Pad (m^3)	42719.12
Number of Windrow	60
Required Area for Composting (m^2)	40320
Pad Dimensions for Composting (m)	720 by 56
Required Area for Curing (m^2)	14307
Pad Dimensions for Curing (m)	511 by 28
Required Area for Storage (m^2)	40888
Pad dimensions for Storage (m)	1460 by 28
Total Area Required (m^2/tonne*yr)	1.33

CHAPTER 6

EXPERIMENTAL OBJECTIVES AND APPROACH

The study was initiated to examine the effects of C:N ratio on bench-scale simulated windrow composting of pulp and paper biosolids. The reactors were operated under a compressive load to simulate compressive settlement in the core of a large-scale windrow. Aerobic conditions were maintained by pumping air through the reactors at periodic intervals and pre-determined flow rates such that oxygen was not a limiting factor. Treatments of various C:N ratios were examined and compared relative to each other. Free air space, temperature, volatile solids reduction and compost stability/maturity were the major parameters used in the examination.

In order to satisfy the objectives outlined, each treatment (C:N ratios 90:1, 50:1, 30:1, and 20:1) were run in triplicate in series. Each analysis was performed in quadruplicate unless otherwise indicated in Appendix D.

6.1   FEEDSTOCK COLLECTION AND PREPARATION

The pulp and paper biosolids, and bark were collected from the PFPC on December 15, 1997. The biosolids consisted of combined sludges: 41% from primary effluent treatment; 21% from secondary effluent treatment; and 39% from deinking processes (wet basis). The biosolids were collected as they came off the belt press machine and the bark was collected from the chute leading to the steam generation boilers. The biosolids and bark were collected in sealed plastic buckets, and stored at 4°C to minimize microbial decomposition.

After collection, the bark was shredded and sieved to the desired particle size of 2.4 to 9.6mm as recommended by Haug (1993). The shredder used was a Crary BearCat Chipper/Shredder, Model 530. US standard sieves, Mesh No. 3/8" (bore diameter 2.38mm) and Mesh No. 8 (bore diameter 9.57mm) were used to achieve the required particle size. The feedstock prepared bark was then stored at 4°C for future use as the composting amendment.

6.2 BENCH SCALE REACTOR CONFIGURATION

Four reactors were run simultaneously, each with a different C:N ratio. The reactors are illustrated in Figures 6-1 and 6-2. Each reactor was placed in the insulating box as illustrated in Figure 6-3 and 6-4 in order to minimize heat loss to the environment. The wooden insulating box was filled with multiple sheets of rigid styrofoam. The insulating box was contained within a temperature-controlled chamber (Figure 6-5). The reactors were setup such that temperature and airflow could be monitored and controlled. Each reactor had its own thermocouple link and air supply. Temperature was measured twice daily using a Fluke 52 K/J thermometer. A ChronTrol XT timer was employed so that at predetermined intervals, a pump supplying air to each reactor was turned on for a set amount of time. The pumping equipment used were Masterflex speed controllers and 6-600 rpm pumps by Cole Parmer Instrument Co.. A plastic flask filled with distilled water within the temperature-controlled chamber was used for each reactor such that air being pumped into the reactor would first pass through this flask. The purpose of this water filled flask was to increase the water partial pressure, thereby maintaining the moisture content within the reactor, and also to minimize heat loss due to aeration. Therefore the

air was humidified and heated to approximate reactor conditions in order to minimize any environmental disturbances. A schematic of this setup is illustrated in Figure 6-6 and shown in photograph in Figure 6-7.
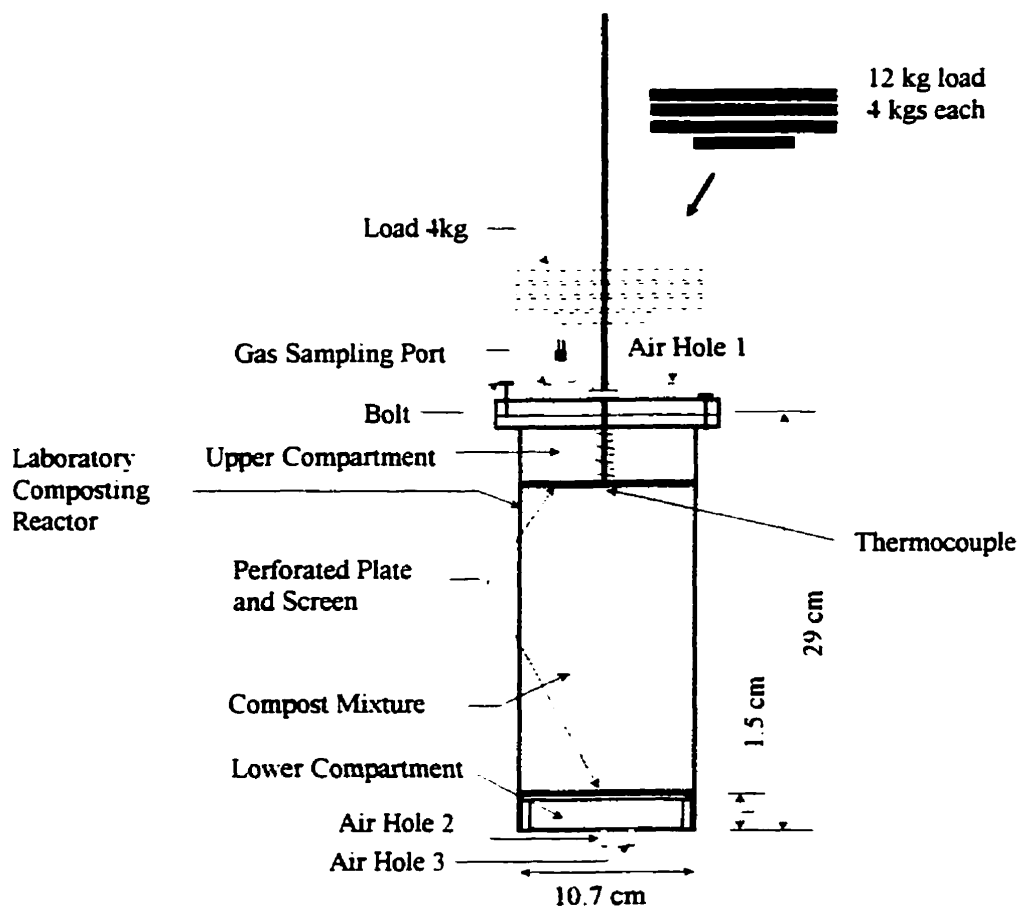
Figure 6-1: Schematic Diagram of Compost Reactor (Chen 1997).

Figure 6-2: Bench Scale Composting Reactor.
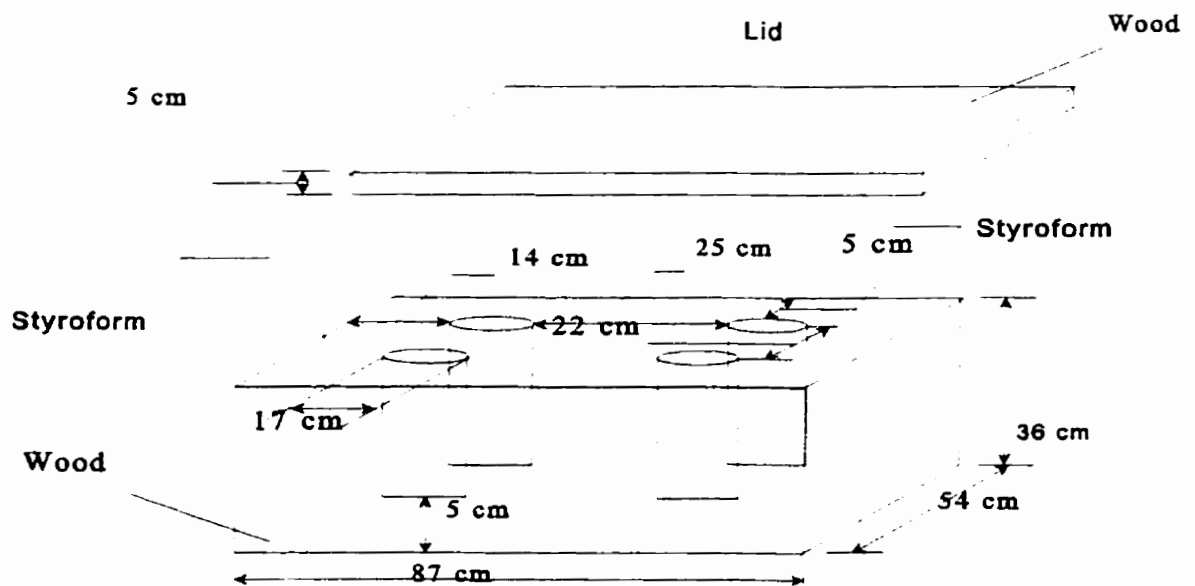
Figure 6-3: Schematic of Reactor Insulating Box (Chen 1997).

Figure 6-4: Compost Reactor Insulating Box.

Figure 6-5: Temperature Controlled Chamber.
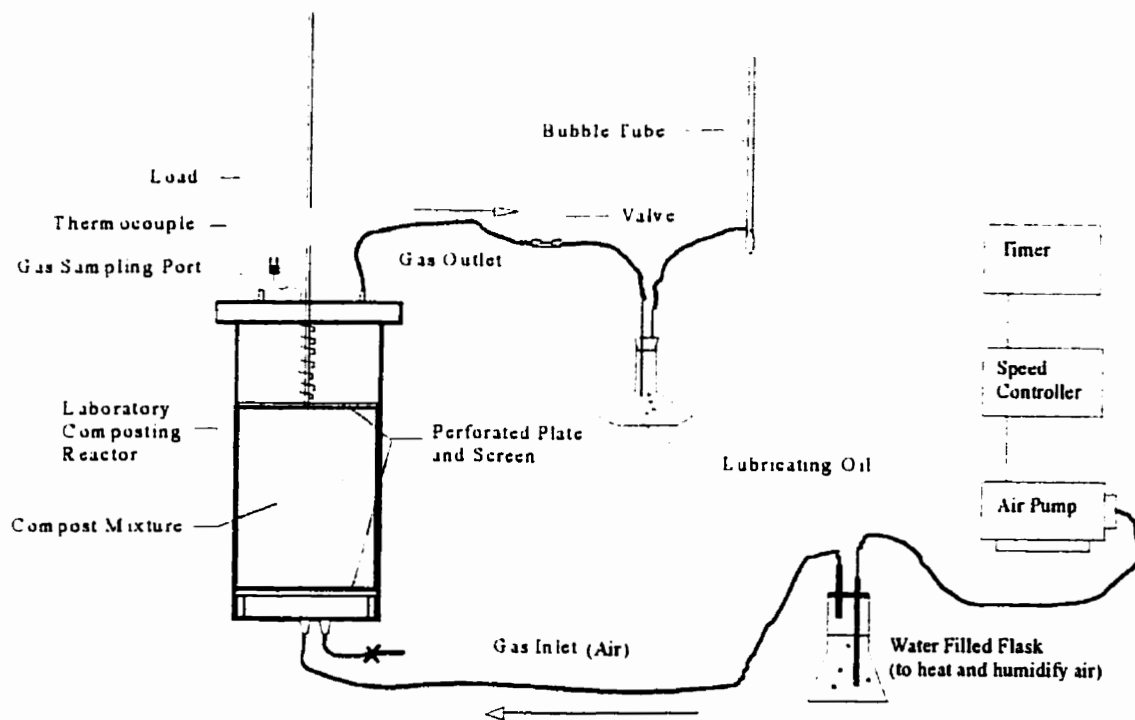
Figure 6-6: Schematic Diagram of Laboratory Compost Reactor Setup (Chen 1997).
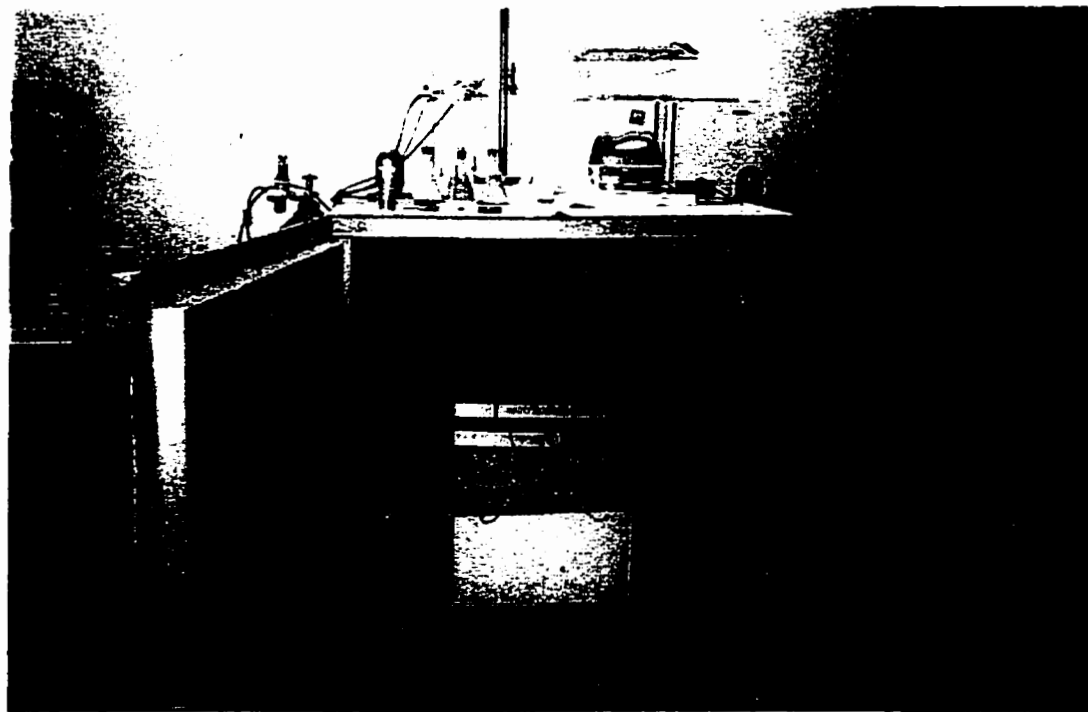
Figure 6-7: Experimental Setup.

6.3 COMPRESSIVE LOAD & OXYGEN REQUIREMENTS

Compressive loads were applied to each reactor to simulate the compressive settlement on a large-scale windrow. A windrow of 3.7 meters in height was selected for the simulation. Suggested windrow pile height is between 6 and 12 feet (1.8 to 3.7 m) (WEF 1995), the maximum of this range was used to simulate a windrow with minimal heat loss in Manitoba climate. This would decrease the surface to volume ratio. The stress caused by the weight of the feedstock at a maximum depth, where maximum compressive settlement occurs was calculated using the following equation, where lateral effects are ignored:

$$S = \frac{D_{wb} \times h \times 9.8}{1000} \qquad \text{(WEF 1995)} \qquad [6\text{-}1]$$

Where S is the compressive stress on the compost of the pile (kPa); D_{wb} is the wet bulk density of the compost (363 kg/m^3); and h is the height from the top of the pile to the center of the section under investigation (3.6 m) as shown in Figure 6-8.

The internal cross section of the reactor was then calculated to determine the load required for each reactor using the following equation:

$$A = \frac{\pi \times d^2}{4} \qquad [6\text{-}2]$$

Where A is the internal cross sectional area of the reactor (cm^3); and d is the inner diameter of the reactor (cm).

The total load on the reactor can the be calculated by the following equation:

$$L = \frac{S \times A}{9.8 \times 10} \qquad\qquad [6\text{-}3]$$

Where L is the total load on the reactor (kg).

The weights used were each 4 kg, therefore, three 4 kg weights were used for each reactor, making a total weight of 12 kg each.
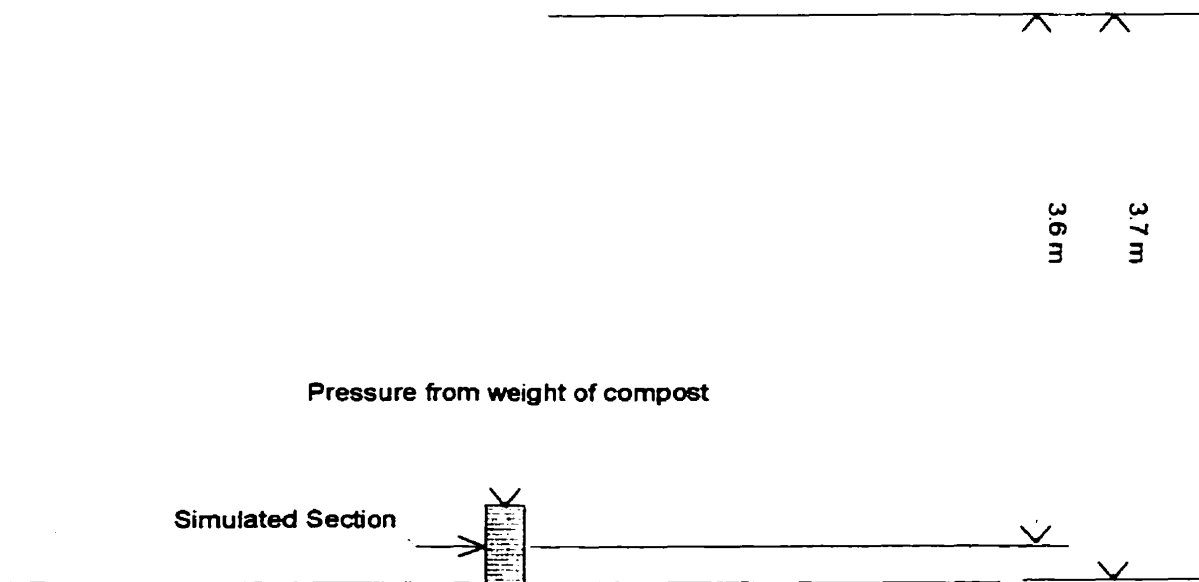
Figure 6-8: Schematic Diagram of Windrow Composting Pile and Section Simulated by Bench Scale Reactors.

Air was supplied to each reactor such that oxygen was not a limiting factor in the decomposition of organic matter during composting. Detailed air requirement calculations are included in Appendix E. The estimated chemical formula of the feedstock (without nitrogen addition) is $C_{511}H_{810}O_{353}N_6S$. It was expected that 0.193 kg of the initial 0.9722 kg of feedstock would theoretically undergo biological volatile solids (BVS) conversion. Therefore 1.35 kg of O_2 was required per kg of BVS converted, translating into 1860 litres of air with a safety factor of 2. In order to minimize moisture and heat loss through aeration, air was pumped through each reactor for five minutes each hour. This interval aeration coupled with the temperature controlled water filled flasks, worked well in minimizing disturbances due to aeration. At this mentioned pumping interval, 15 mL of air was required per second per reactor in order to satisfy the oxygen requirements of the reactors. The aeration flow rate was measured using a bubble tube (sbf-10 Soap Bubble Flowmeter 10cc, Chromatographic Specialties Inc.) using an erlenmeyer flask filled with lubricating oil (Motomaster Formula 2000, 20w50) in order to isolate the outside air.

6.4   COMPOST RECIPE

The amendment used to bulk up the biosolids to create a suitable feedstock for composting was shredded bark. The bark was mixed with the biosolids at a ratio designed to optimize the moisture content of the mixture while providing suitable free air space characteristics. The feedstock materials (biosolids and bark) were mixed as is, with respect to moisture content, where no drying or moisture adjustment was used. This was done to simulate the mixing of the feedstock on a large-scale, without the need for

feedstock moisture adjustment prior to mixing. Therefore the biosolids coming directly off the belt press could be mixed directly with shredded bark from the woodroom. Both the biosolids and the bark were analyzed for moisture content, nitrogen content, C:N ratio and wet bulk density, in order to determine the compost recipe. Feedstock material characteristics are illustrated in Table 6-1. An initial moisture content of 60% was selected to optimize the composting process. Using the following equation, the required amount of amendment (bark) was calculated:

$$\text{Bark Required (kg/kg)} = \frac{MC_{biosolids} - MC_{target}}{MC_{target} - MC_{bark}} \qquad [6\text{-}4]$$

Where the amount of bark required is measured in kg of bark per kg of biosolids; $MC_{biosolids}$ is the moisture content of the biosolids (%); MC_{bark} is the moisture content of the bark (%); and MC_{target} is the target moisture content (60%). Using the data in Table 6-1, the resulting amount of amendment required is 0.75 kg of bark per kg of biosolids. This resulting amendment requirement was used for each reactor of each experimental run. The resulting C:N ratio was calculated from equation 6-5.

$$C:N_{mix} = \frac{N_b \times C:N_b \times TS + N_a \times C:N_a \times TS_a \times R}{N_b \times TS_b + N_a \times TS_a \times R} \qquad [6\text{-}5]$$

Where $C:N_{mix}$, $C:N_b$, and $C:N_a$ are the C:N ratios of the composting mixture, biosolids and amendment (bark) respectively; N_b, and N_a are the nitrogen contents of the biosolids

and amendment (bark) respectively (dry weight grams); TS_b, and TS_a are the moisture contents of the biosolids and amendment (bark) respectively (%); and R is the amendment ratio (0.75 kg bark/kg biosolids). The resulting C:N ratio of the composting mixture is 91.65.

Table 6-1: Feedstock Material Characteristics.

Material	% MC	% N (db)	C:N	Wet Bulk Density (kg/m³)
Biosolids	66.58	0.87	47.9	440
Bark	51.21	0.21	257.5	200

This study investigated the effects of composting at various C:N ratios. The C:N ratios investigated were 90:1, 50:1, 30:1, and 20:1. In order to achieve these C:N ratios, nitrogen addition was required. The required amount of nitrogen needed was determined using the following equation:

$$R_c = \frac{TKN_M \times TS_M - (TKN_A \times TS_A \times R_A + TKN_B \times TS_B \times R_B)}{TKN_C \times TS_C}$$

[6-6]

Where TKN_M, TKN_A, TKN_B and TKN_C are the TKN contents of the composting mixture, amendment (bark), biosolids and fertilizer respectively (g N/g TS); TS_M, TS_A, TS_B and TS_C are the total solids of the composting mixture, amendment (bark), biosolids and fertilizer respectively (g dry solids/g total); and R_A, R_B, and R_C are the ratio of amendment (bark), biosolids, and fertilizer (%) in the composting mixture. Table 6-2 shows the resulting fertilizer requirements for each C:N ratio investigated.

Table 6-2: Fertilizer Addition Requirements

Desired C:N Ratio	%N in Fertilizer	%N in Biosolids/Bark Mixture	% Carbon in Biosolids/Bark Mixture	% Fertilizer Required
90:1	32	0.53	47.96	0
50:1	32	0.53	47.96	0.54
30:1	32	0.53	47.96	1.34
20:1	32	0.53	47.96	2.34

6.5 REACTOR OPERATION AND DAILY MONITORING

Each treatment was run in series in triplicate with C:N ratios of 90:1, 50:1, 30:1 and 20:1. Reactors were configured as described in Section 6.2. Analysis consisting of solids, organic content, TKN, particle densities, and bulk densities were performed before and after composting. Air was supplied to each reactor as described in Section 6.3. During the composting period, both settlement due to compaction and reactor temperature were measured twice daily (Appendix D, pp. 176, 177, 194, 195, 212, & 213). Each reactor had an initial compost height of approximately 25 cm. At time zero, a 12 kg load was applied to each reactor causing compressive settlement over the course of composting. Twice daily a measurement was made concerning the height of the compost in the reactor. This height was recorded for later translation into compressive settlement and free air space reduction. The temperature of the chamber and reactors were initially ambient. At the start of composting, the chamber temperature was set to 35°C. Within a day, each reactor temperature had raised to the chamber temperature or greater. Throughout the remainder of the composting phase, each reactor was measured for temperature twice daily. The chamber temperature was adjusted at each temperature reading to approximately 1°C below the lowest reactor temperature. The experimental

run was considered to be complete when the reactors dropped to a temperature of 35°C. Composting time therefore fell within the range of approximately 16 to 18 days.

6.6   EXPERIMENTAL ANALYSIS

Several analyses were performed in the characterization of the feedstock material and final compost. These analyses included total solids (TS), moisture content (MC), volatile solids (VS), fixed solids (FS), organic carbon (OC), total Kjeldahl nitrogen (TKN), C:N ratio, particle density, bulk density (wet and dry), particle distribution and compost stability.

The TS, VS, and FS analyses were determined using standard method 2540 B & E (APHA 1995). The MC and organic carbon were calculated using equations 6-6 and 6-7 respectively.

$$MC = 1 - TS \qquad\qquad [6\text{-}6]$$

$$OC = \frac{1 - FS}{1.8} \quad \textit{(Haug 1993, Liao et al. 1995)} \qquad [6\text{-}7]$$

The TKN analysis was conducted by following the "Micro-Kjeldahl Digestion Followed by Steam Distillation: Without Pretreatment to Include NO_2^- and NO_3^- Quantitatively" method (Carter 1993). The samples were processed prior to TKN analysis as follows. The material was allowed to air dry for a one week period. The material was then put into a blender for 6 one minute intervals, allowing time for the blender and material to cool between each blending interval. The TS, VS, and FS analyses were again

conducted, this time using the TKN prepared samples in order to convert the raw experimental wet based TKN results to final dry based results.

The particle density (D_p) analysis was conducted using the Pycnometer Method (Klute et al. 1986), and the bulk density analysis was conducted using the Core Method (Carter 1993). The particle size distribution was determined by sieving the material through standard US sieves of 1/2, 1/4, and 1/8 inch (12.7, 6.4, and 3.2 mm) in size and weighing the percentage of the total material in each size classification. The compost stability was analyzed by Norwest Laboratories using carbon dioxide evolution as a means of measuring the respiration rate, Method S99 (Bartha and Palmer 1965).

CHAPTER 7

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental program consisted of three experimental runs, run in series as described in Chapter 6. The results of the investigation are reported in this chapter, as well as discussion of the results. All raw experimental data is contained in Appendix D.

7.1   PRELIMINARY FEEDSTOCK CHARACTERIZATION

The TS, MC, VS, FS, OC, TKN, and C/N ratio for the PFPC bark and biosolids are shown in Table 7-1. All solids data was determined using standard methods 2540 B and E (APHA, 1995). The OC was calculated using equation 6-7, where OC and FS are based on the dry weight fraction (Haug 1993, Liao 1995).

Table 7-1: Summary of Feedstock Characteristics.

Parameter	Biosolids			Bark		
	# of samples (n)	Mean (x)	Standard Deviation (s)	# of samples (n)	Mean (x)	Standard Deviation (s)
MC (% wb)	4	66.58	0.12	4	51.21	0.98
VS (% db)	4	75.29	0.24	4	96.80	0.13
OC (% db)	4	41.83	0.13	4	53.78	0.07
TKN (% db)	4	0.87	0.04	4	0.21	0.01
C:N	4	47.90	2.43	4	257.40	16.90

The C:N ratio was calculated using the resulting OC and TKN results, where TKN was determined by micro-Kjeldahl digestion followed by steam distillation (Carter, 1993).

The particle density, bulk density, porosity, volumetric water content and free air space are shown in Table 7-2. The particle density was determined using the pycnometer method (Klute 1986), the bulk density was determined using the core method (Carter 1993), and the remaining properties were calculated using the following equations:

$$n = 1 - \frac{D_{db}}{D_p}$$ [7-1]

Where n is the porosity (cm^3/cm^3), D_{db} is the dry bulk density (g/cm^3), and D_p is the particle density (g/cm^3).

$$\theta = \frac{MC \times D_{db}}{D_w}$$ [7-2]

Where θ is the volumetric water content (cm^3/cm^3), MC is the moisture content (%), and D_w is the density of water (g/cm^3).

$$FAS = n - \theta$$ [7-3]

Where FAS is the free air space (cm^3/cm^3).

Table 7-2: Density and FAS characteristics of Feedstock.

Parameter	Biosolids			Bark		
	# of samples (n)	Mean (x)	Standard Deviation (s)	# of samples (n)	Mean (x)	Standard Deviation (s)
D_{wb} (g/cm^3)	6	0.44	0.01	6	0.20	0.01
D_{db} (g/cm^3)	4	0.17	0.00	4	0.11	0.00
D_p (g/cm^3)	8	1.75	0.24	8	0.82	0.08
n (ml/ml)	4	0.91	0.00	4	0.87	0.05
θ (ml/ml)	4	0.11	0.00	4	0.06	0.00
FAS (ml/ml)	4	0.80	0.01	4	0.82	0.05

The results obtained from the feedstock analysis were used to determine the quantity of nitrogen fertilized required to adjust the C:N ratio to values of 90:1, 50:1, 30:1, and 20:1. The fertilizer used was the "Park Special", produced by ICI Canada Inc. Specifications of this fertilizer are given in Table 7-3. The required fertilizer addition was calculated using equation 6-6.

Table 7-3: Nitrogen Fertilizer Specifications.

Manufacturer	ICI Canada Inc.
Fertilizer Type	Park Special (34-4-8)
Total Nitrogen (% N) - Manufacturers Guaranteed Minimum Analysis	32
N derived from S.C.U.[a] ((sulfur coated urea) (%) – Manufacturers Guaranteed Minimum Analysis	12.8
Ammoniacal N (from monoammonium) (%) – Manufacturers Guaranteed Minimum Analysis	0.9
Available Phosphoric Acid (from phosphate) (% P_2O_5) – Manufacturers Guaranteed Minimum Analysis	4.0
Soluble Potash (from muriate of potash) (% K_2O) – Manufacturers Guaranteed Minimum Analysis	8.0
Sulfur (% S) – Manufacturers Guaranteed Minimum Analysis	5.0
Nitrogen from other sources (urea)	18.3
TKN (%) – Analyzed (see Appendix D)	31.14

At target moisture content of 60%, 0.75kg of bark is required per kg of biosolids. This results in a calculated C:N ratio of 90:1 with no nitrogen addition. In order to increase the C:N ratio to values of 50:1, 30:1 and 20:1, the amount of fertilizer required was 0.54, 1.34, and 2.34 % respectively.

Comparing reported literature values with those determined through experimental work, it was found that the PFPC biosolids analyzed fell within the typical ranges of pulp and paper mill sludges (Table 7-4) for MC, VS, OC, TKN, and wet bulk density.

Table 7-4: Comparison of Experimental Biosolids Characteristics with Literature Values for General Pulp and Paper Mill Biosolids.

		MC (%wb)	VS (%db)	OC (%db)	TKN (%db)	Wet Bulk Density (kg/m^3)
Biosolids	Experimental	66.58	75.29	41.83	0.87	440
	Literature	52-88	35-93	19.4-54.7	0.07-5.94	369-930

Literature values (Phenicie and Maher 1985)

7.2 COMPACTION AND FREE AIR SPACE

Each composting reactor was loaded with 12 kg weights to simulate the compressive settlement within a large scale windrow. The 12 kg loading was determined by simulating the stress at the bottom of windrow 3.7 meters in height (the maximum windrow height as recommended by the United States Environmental Protection Agency) (WEF 1995) where the stress is at a maximum.

The 12 kg load was applied to each reactor from time zero and held throughout the course of the experiment. The compaction results from each of the three experimental runs were averaged for each C:N ratio investigated as illustrated in figure 7-1. The results indicate that for each treatment, over 70 % of the maximum total compaction occurred within the first 30 minutes of reactor loading, and approximately 95% of the maximum total compaction occurred within 7 days of reactor loading. At the end of the experiment, the composting mixture had undergone a compressive settlement of approximately 55% representing a significant volume reduction. This reduction in volume can be viewed as an important design parameter in the design of a windrow composting operation. However, it should be noted that the volume reduction of the compost mixture in the reactor is representative of a section at the bottom of the windrow only, and that volume reduction due to compressive settlement will be significantly less for the whole windrow.

Table 7-5 shows the wet and dry bulk densities before and after composting for each C:N ratio investigated. The data shows that wet and dry bulk densities increased after composting and that the densities generally increased as C:N ratios decreased. This can be attributed to a greater degree of decomposition in reactors with a lower C:N ratio. As the organic matter decomposed, the solid particles are broken down both chemically and physically through biochemical processes. This physical breakdown of the solid particles is responsible for the increase in bulk densities.
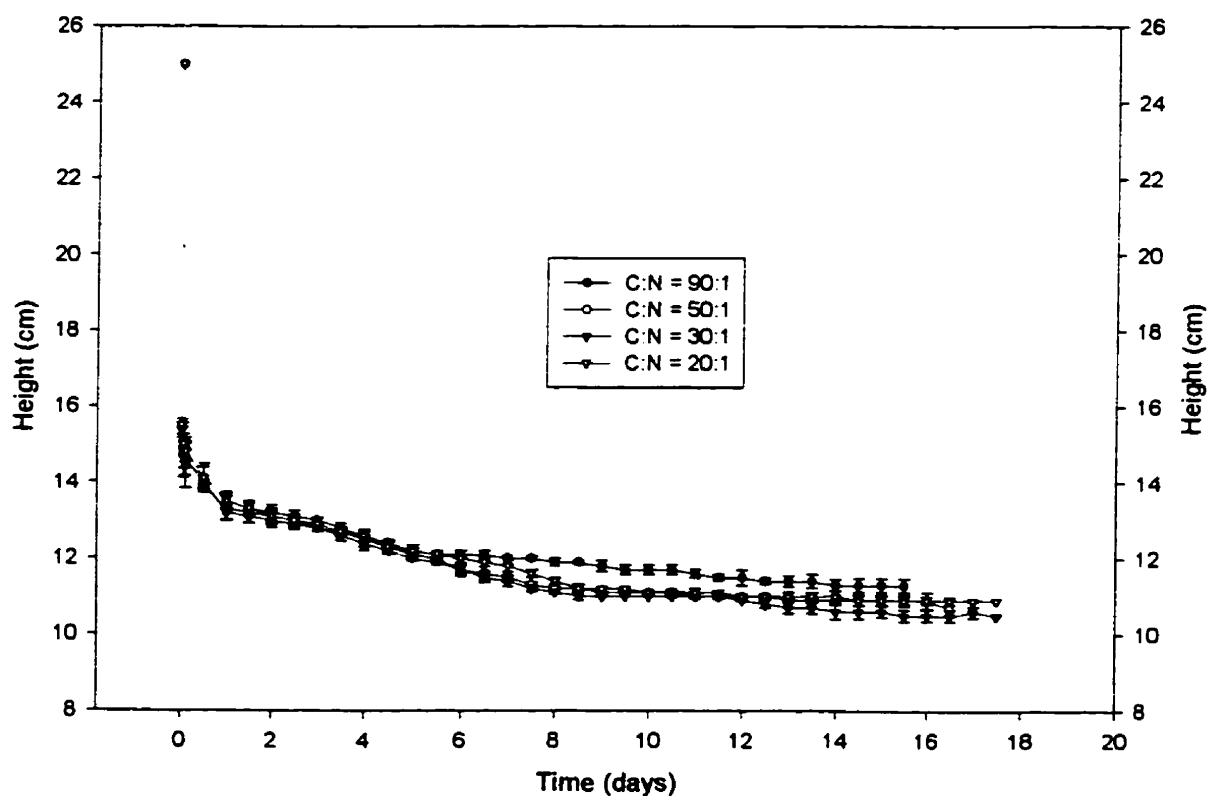
Figure 7-1: Mean Compaction Results.

Table 7-5: Bulk Density Prior to and After Composting.

	C:N ratio	# of Samples (n)	Mean (x)	Standard Deviation (s)
Wet Bulk Density – Prior To Composting (kg/m^3)	90:1	6	322	4
	50:1	6	328	12
	30:1	6	320	9
	20:1	6	320	11
Dry Bulk Density – Prior To Composting (kg/m^3)	90:1	6	155	8
	50:1	6	160	11
	30:1	6	157	10
	20:1	6	160	15
Wet Bulk Density – After Composting - Non-Compacted (kg/m^3)	90:1	6	403	14
	50:1	6	423	12
	30:1	6	435	14
	20:1	6	442	15
Dry Bulk Density –After Composting - Non-compacted (kg/m^3)	90:1	6	165	14
	50:1	6	173	14
	30:1	6	178	15
	20:1	6	178	12
Wet Bulk Density – After Composting - Compacted (kg/m^3)	90:1	3	674	21
	50:1	3	692	15
	30:1	3	726	12
	20:1	3	709	11
Dry Bulk Density – After Composting - Compacted (kg/m^3)	90:1	3	255	3
	50:1	3	257	5
	30:1	3	269	6
	20:1	3	262	5

The compressive settlement of the composting mixture is of great importance due to its effect on the free air space within the compost. The free air space provides oxygen transfer throughout the network of solid particles and water molecules. If there is too much water and too little free air space, oxygen transfer is greatly restricted and aerobic composting is hindered. Likewise, if the free air space is large and there is not enough water, microbial kinetics will be slowed and composting activity will decline due to lack

of moisture, and lack of contact between water particles, air, and solid particles (Haug 1993). More fibrous and friable materials are capable of maintaining higher moisture contents while retaining adequate free air space. Therefore, not only is the bark amendment used to adjust the moisture content of the composting mixture, but to provide structural integrity so that the free air space is reasonably maintained, increase the size of pore spaces, and allow easier air movement through the mixture.

Free air space was calculated from the compaction data using the following equation:

$$FAS_i = \frac{FAS_0 \times V_0 - (V_0 - V_i)}{V_i}$$

[7-4]

Where FAS_i is the free air space of the composting mixture with loading (cm^3/cm^3), FAS_0 is the free air space of the composting mixture initially without loading (cm^3/cm^3), V_i is the volume of composting mixture with loading (cm^3), and V_0 is the initial volume of the composting mixture (cm^3).

Figure 7-2 illustrates the mean free air space results averaged for each treatment over the experimental composting period. The figure demonstrates that the initial FAS reduction due to loading occurs within the first half hour upon loading, and accounts for approximately 75% of the total FAS reduction. Over the remaining 15 to 18 days, the remaining 25% of the total reduction occurs. The total FAS reduction is approximately 75% of the initial value. The data indicates that the difference in free air space between various treatments follows no noticeable trends. It was found that FAS decreased with C:N ratios of 90:1, 30:1, 20:1 and 50:1 respectively, therefore no trend. It is believed that the C:N ratio was not responsible for the differences in FAS. One potential explanation

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is that each treatment (C:N ratio) was run in the same reactor for each experimental run. Therefore, the FAS differences are thought to be a function of the reactor, while the C:N ratio (addition of nitrogen), had no observable effect on the FAS of the composting mixture.

Haug found that the optimum FAS in a composting mixture was 30%, and 95% of the maximum oxygen consumption rate was maintained when FAS was between 20 and 35% (Haug 1993). The experimental data from this study shows that the FAS in the composting reactors remained between 20 and 35% for nearly the duration of the experiment. Therefore, according to Haug (1993), 95% of the maximum oxygen rate was maintained. This also shows the reactors had a good mix. The optimal FAS of 30% was attained approximately 2 days into the composting process. This is an indication of the required turning frequency to maintain optimal aerobic conditions within a windrow. Although the experimental data indicates that a less frequent turning schedule will still provide sufficient aeration with 95% of the maximum oxygen consumption rate being maintained. It is also important to remember that the FAS reduction in the reactors represents a section at the bottom of the windrow at a depth of 3.6 m (Figure 6-8) where the reduction is at a maximum. As well, a windrow is turned periodically thereby increasing FAS upon turning, whereas the reactor contents were left unturned for the duration of the composting period, so FAS underwent continual reduction. However, in this experiment forced aeration was used to ensure oxygen was not limited in any of the reactors (Figure 6-6).
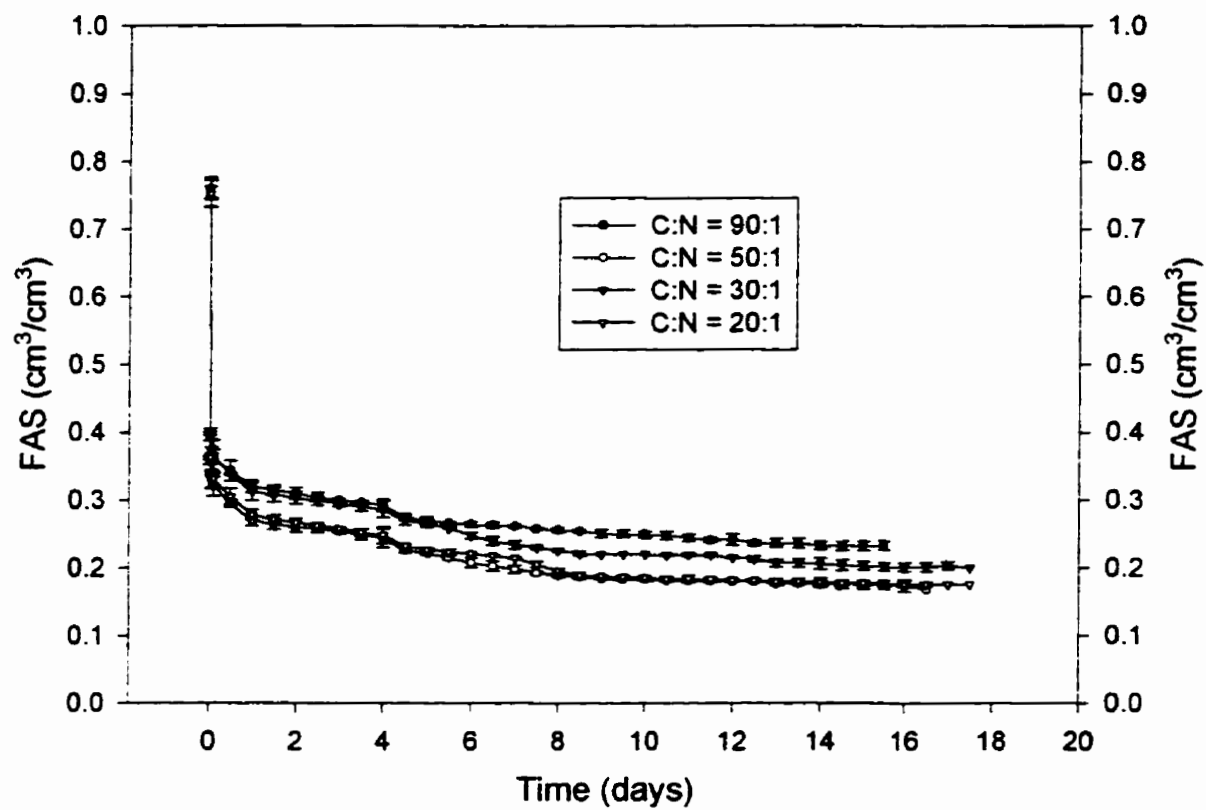
Figure 7-2: Mean FAS Results.

7.3   ODOUR OBSERVATIONS

The odour observations of this experiment were a personal observation. No panel was employed, and all observations were made qualitatively. The odour of the finished compost for each treatment was compared to the other treatments upon completion of each run. After the run was complete, each reactor was opened and smelled for odour. The treatment using no nitrogen addition, with a C:N ratio of 90:1 had a finished compost smell that was sweet and earthy, much more pleasant to the nose than the raw feedstock. The treatment with a C:N ratio of 50:1 had an even stronger sweet/earthy smell than the first, it was very pleasant to smell, with no pungent odour. The treatment with a C:N ratio of 30:1 had an odour which was the most pleasant of all treatments, its odour was similar to the previous two with a more defined sweet/earthy smell. Finally, the treatment with a C:N ratio of 20:1 had a very distinct strong odour of ammonia. Upon immediate opening of the 20:1 reactor, the ammonia smell was so strong that it caused choking and watering eyes. These observations occurred in each experimental run.

Undoubtedly, the most difficult problem in common composting operations is the control of odours. Odours are a nuisance to neighboring receptors (Epstein 1997). The low C:N ratio of 20:1 used in the experiment caused a excess release of ammonia into the vapor phase from the aerobic decomposition of proteins and amino acids. The conversion of ammonium into ammonia gas is a function of pH, where at higher pH's, ammonium is converted into ammonia. This is consistent with that reported by Epstein (1997) who stated that feedstocks with low C:N ratios (lower than 20:1) release ammonia during composting. Luckily, ammonia is usually considered to be a relatively minor odourant

for a composting facility, as ammonia has a relatively high threshold odour concentration and dilutes rapidly to below detection (Haug 1993).

7.4 TEMPERATURE

The temperature rise observed in actively composting wastes is attributed to exothermic reactions associated with respiratory metabolism (Tchobanoglous et al. 1993). Therefore heat output is a function of microbial activity (Epstein 1997). In a windrow composting system, windrow temperatures decrease after 10 to 15 days as the readily biodegradable organic material is oxidized (Tchobanoglous et al. 1993). The reactors used in this study simulated windrow temperature conditions, reaching a maximum temperature at approximately 8 days with temperatures in the thermophilic range. The mean temperature profiles over time for the four different C:N ratio treatments are illustrated in Figure 7-3. In general, the profile shows the lower the C:N ratio, the greater the maximum temperature attained. The mean maximum temperatures reached were 49.1, 50.8, 52.2, and 52.6°C for C:N ratios of 90:1, 50:1, 30:1 and 20:1, respectively. The rate of decomposition of organic matter is affected by the time-temperature relationship and is therefore important for the production of a stable and mature product for consumer use (Epstein 1997).

Figure 7-4 illustrates the results of degree days above chamber temperature versus time, where degree days is the temperature difference between reactor and chamber temperature (°C) multiplied by the composting period (days). Degree days is essentially the area between the reactor temperature and chamber temperature in Figure 7-3, and represents the relative heating efficiency of each reactor. Through linear regression it is

illustrated that reactor temperature above chamber temperature increases linearly as the C:N ratio decreases. However, due to the lack of data points, this linear relationship may or may not be consistent at lower C:N ratios. Since the heat output is a function of microbial activity, the temperature data indicates that the decomposition of biodegradable organic matter would be greater in the treatment using lower C:N ratios. This reasoning was found to be true for this study, where, the treatments using lower C:N ratios, and hence greater temperatures, had a higher degree of respiratory activity as determined by volatile solids destruction. Jackson and Line (1997) support these findings, stating that temperature alone had a marked influence on respiratory activities and rate of paper mill sludge decomposition during composting. Their bench scale experimental work showed that at composting temperatures of 55°C, the decomposition rate occurred faster than at 35°C. When composting at 35°C, a 30-50 day delay in maturation was observed in comparison to composting at temperatures of 55°C, as well as a slower rate of CO_2 formation and an extended period of O_2 consumption. Therefore, the increased rate of paper mill sludge decomposition with increased temperatures can be directly related back to the C:N ratio of the composting mixture, whereby a compost with a more optimal C:N ratio will produce maximum heat output and an optimal decomposition rate. This decomposition as measured by volatile solids destruction for this study is discussed further in the next section.
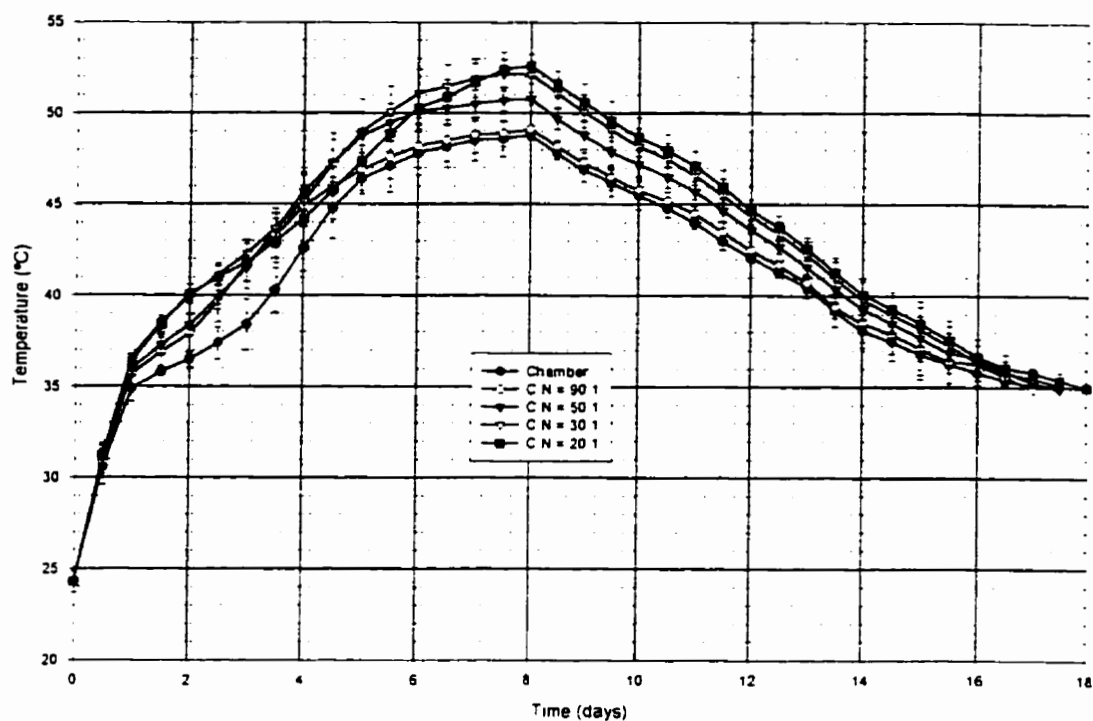
Figure 7-3: Mean Temperature Profile.
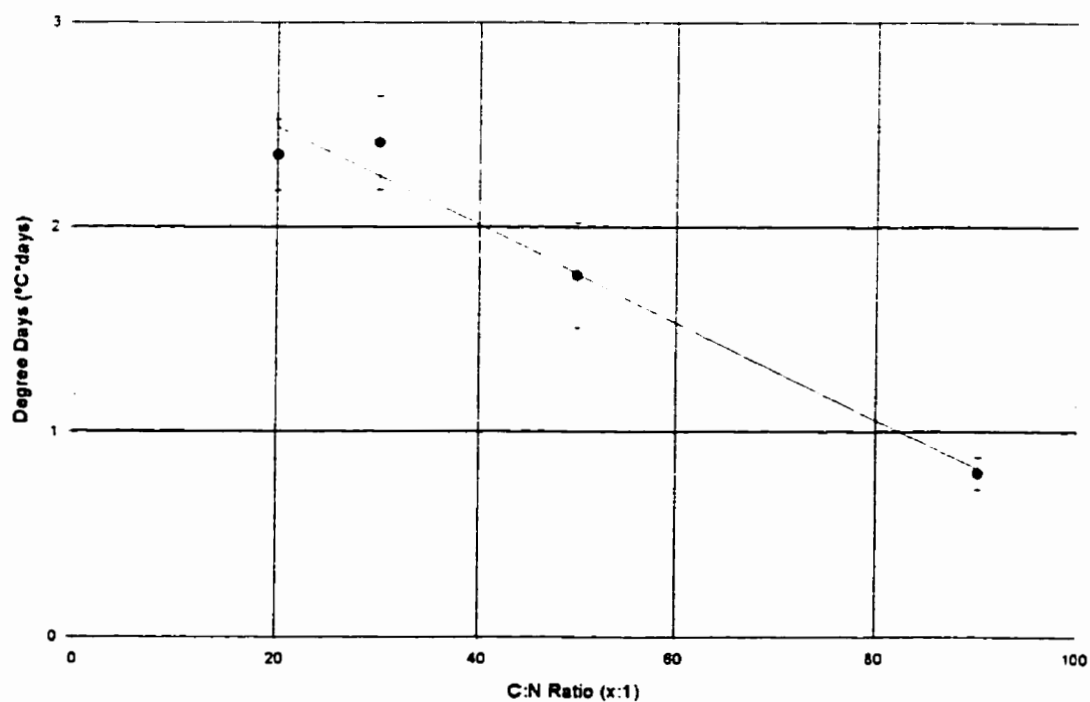
Figure 7-4: Degree Days vs. C:N Ratio – Linear Regression (r^2=0.973).

7.5   VOLATILE SOLIDS REDUCTION

Experimental parameters were controlled such that moisture and oxygen were not limiting factors in the decomposition of the composting mixture. However, nutrients may at times be the limiting material for microbial cell synthesis and growth.

The volatile solids were measured at the beginning and end of the composting period for each treatment. Volatile solids destruction was calculated by using the volatile solids data and dry weight loss of the material through composting as shown in the following equation:

$$VS\ destruction = \frac{VS_0 - VS_i}{VS_0} \times 100 \qquad [7\text{-}5]$$

Where VS_0 and VS_i are the volatile solids content before and after composting (%).

Figure 7-5 illustrates the mean volatile solids reduction for each C:N ratio investigated. The volatile solids destruction increased as the C:N ratio decreased. A linear line can be fit to the data between C:N ratio's of 90:1 to 30:1, indicating a constant slope and linear increase in the volatile solids destruction rate as the C:N ratio approaches optimum. The r^2 value for a linear fit of all four data points is 0.835. From a C:N ratio of 30:1 to 20:1, the slope of the line increases, indicating a higher rate of volatile solids reduction. The maximum mean volatile solids destruction obtained (16.5%), occurred using a C:N ratio of 20:1. Theoretically, the expected maximum biological volatile solids reduction was estimated to be 19.85% (Equation 7-6).

$$\text{Expected BVS Conversion} = W \times TS \times VS \times 0.60 \qquad [7\text{-}6]$$

Where BVS is the biodegradable fraction of the volatile solids (g), W is the weight of the compost mixture (g), TS is the total solids of the mixture (%), VS is the volatile solids of the mixture (%), and 60% of the volatile solids are assumed to be biodegradable. Calculations are presented in Appendix E. Table 7-6 shows the numerical values for each treatment as well as the percentage of the theoretical maximum.
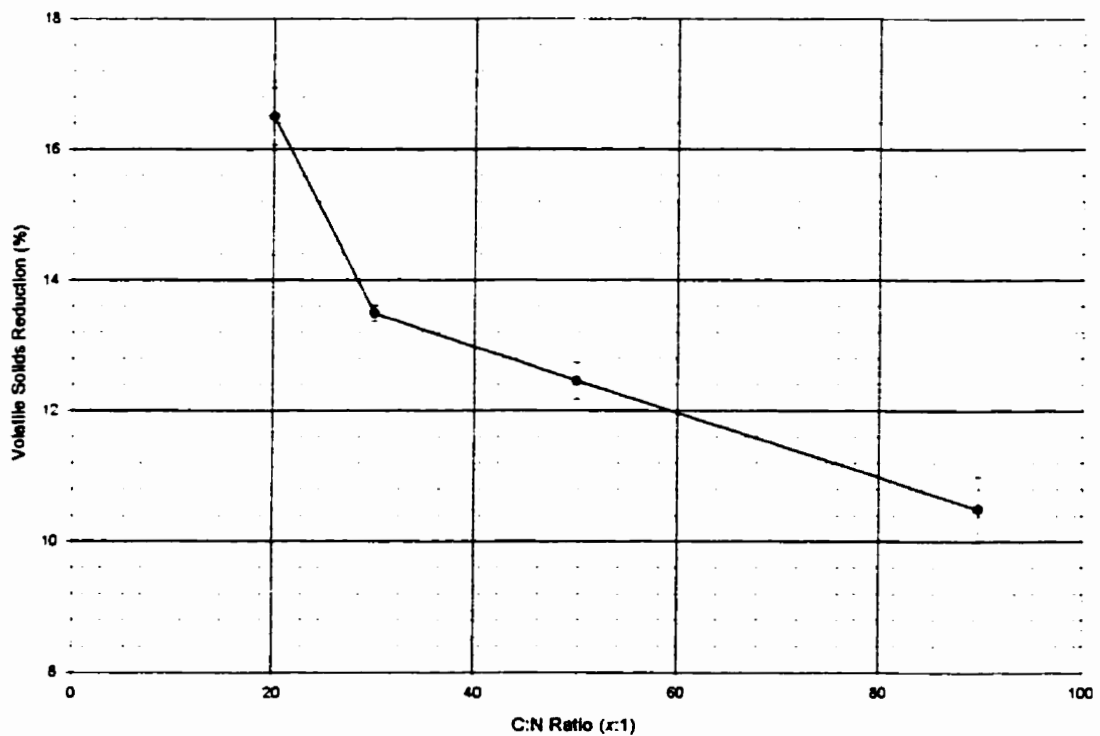
Figure 7-5: Volatile Solids Reduction.

Table 7-6: Comparison of Volatile Solids Destruction to Theoretical Maximum.

	Theoretical Maximum	C:N = 90:1	C:N = 50:1	C:N = 30:1	C:N = 20:1
VS Destruction (%)	19.85	10.50	12.46	13.50	16.51
% of Theoretical Maximum (%)	N/A	52.9	62.8	68.0	83.2

A C:N ratio of 20:1 was the lowest investigated, it is expected that at lower C:N ratios, ammonia is given off, and biological activity is impeded (Tchobanoglous et al. 1993). Jackson and Line (1997) studied the effect of nutrient addition on the composting of pulp and paper mill sludge. At a C:N ratio of 25:1 they were able to achieve a cumulative dry weight loss as CO_2 of approximately 10%. Assuming that all of the carbon in the CO_2 results from the organic carbon in the composting material, and that the volatile solids analysis estimates the carbon content or organic matter of a sample, Jackson and Line (1997) achieved a volatile solids destruction of approximately 18%, using equation 6-7. This compares well with the 16.5% volatile solids destruction achieved in this experiment.

Jackson and Line (1997) also found that dry weight loss during composting occurred at a significantly faster rate at 55°C than 35°C, and that the method of nutrient addition did not have a significant effect on dry weight loss. Therefore, the increase in volatile solids reduction correlates to the increase in temperature observed. The volatile solids destruction rate can be described as a single-peak curve as a function of composting temperature. However, there is a trade off between bioactivity and pathogen destruction.

At temperatures greater than 55°C pathogen destruction is greatest, however, bioactivity is hindered as many of the microorganisms responsible for the destruction of volatile solids are killed.

7.6 PARTICLE SIZE DISTRIBUTION

Particle size distribution is important for optimum composting results as well as intended final compost use. Too many fines may be undesirable to the structure of a composting mixture, leading to decreased free air space, and therefore possibly a reduced rate of decomposition. Large size particles may also cause problems due to the need for screening of the final compost product. For example, if the compost is intended for general horticultural use, or as a top dressing on lawns and gardens, the maximum particle size should be less than or equal to 10 millimeters (0.39 in) (Haug 1993). Table 7-7 shows the particle size distribution of the feedstock before composting, as well as the particle size distribution of each reactor from the final run of composting. Particles greater than 1/4 inch were reduced from over 67% to less than 45% through composting, particles with sizes ranging between 1/8 to 1/4 inch (3.18 to 6.35 mm) were increased from about 26% to 40% through composting, and particles less than 1/8 inch (3.18 mm) increased in distribution from about 6% to over 15%. Figures 7-6 to 7-10 show the compost distributed into the three particle sizes for each C:N treatment. The increase in distribution towards the smaller particle sizes compared to the precomposted mixture is apparent. This shift towards a greater distribution of smaller particles is the result of the decomposition of organic matter, and results in a more suitable product for marketing.
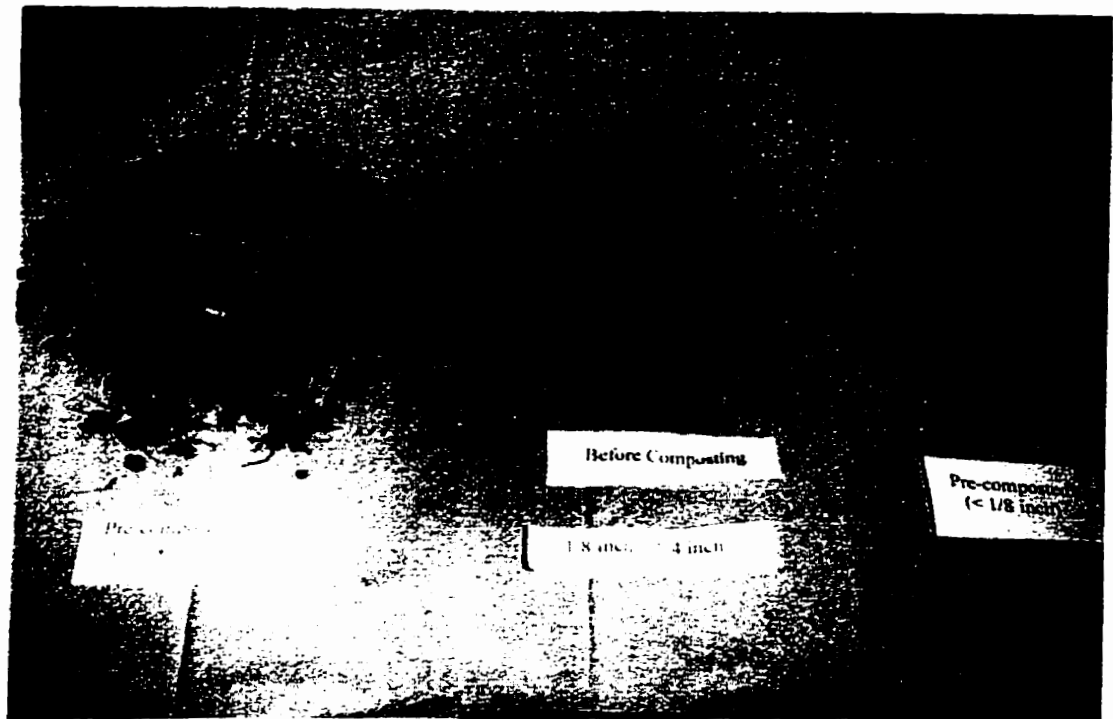
Figure 7-6:   Particle Size Distribution - Precomposted
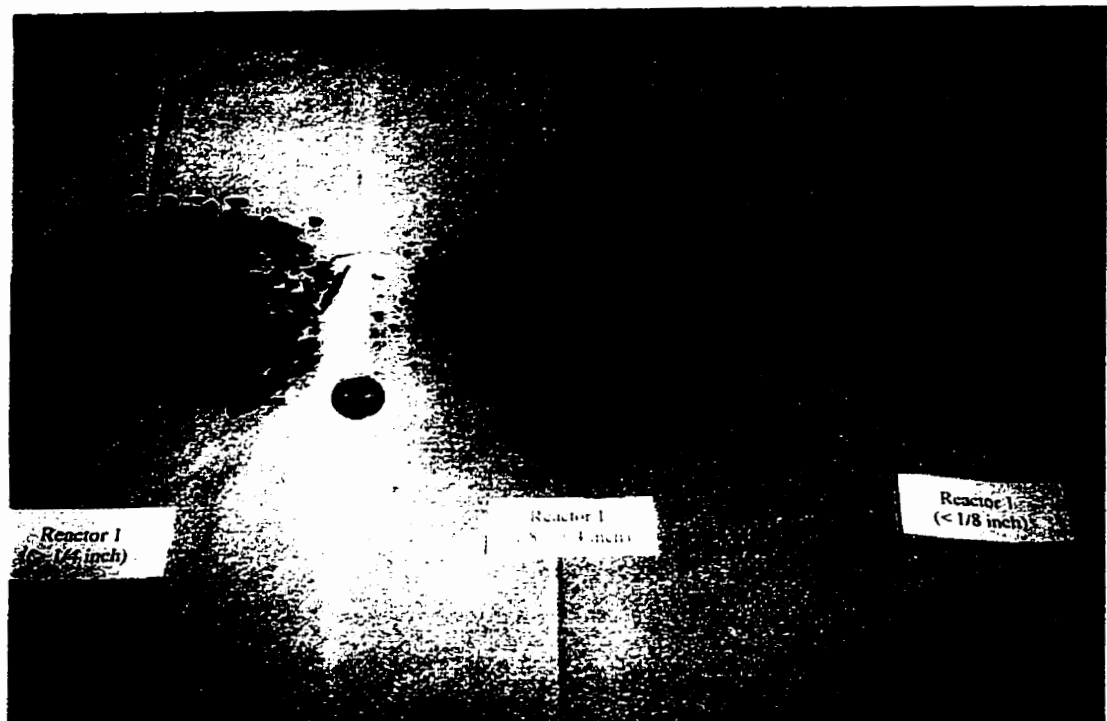
Figure 7-7:   Particle Size Distribution – C:N=90:1

Figure 7-8: Particle Size Distribution – C:N=50:1

Figure 7-9: Particle Size Distribution – C:N=30:1
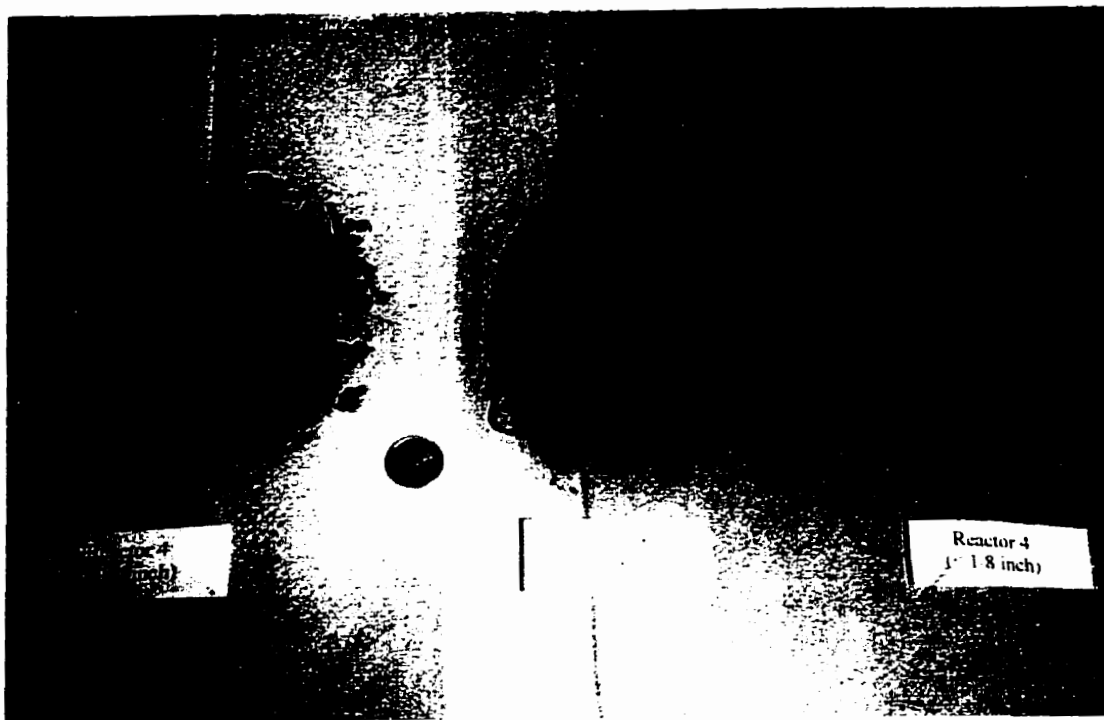
Figure 7-10: Particle Size Distribution – C:N=20:1

Table 7-7: Experimental Particle Size Distribution – wet basis (Final Run).

Sample	>1/4" (%)	1/8-1/4" (%)	<1/8" (%)
Pre-Composted	67.52	26.05	6.44
Composted (C:N=90:1)	43.75	40.39	15.86
Composted (C:N=50:1)	48.53	38.94	12.53
Composted (C:N=30:1)	44.35	39.80	15.84
Composted (C:N=20:1)	42.73	39.11	18.17

7.7 COMPOST STABILITY AND MATURITY

In order for compost to have marketable value, it must be mature, or stable. The best indication of stability, which represents the state of microbial activity (the degree to which the biodegradable fraction of VS has been converted), is the measurement of respiration. Respiration can be measured either by oxygen uptake, or carbon dioxide evolution. Stability measurements should be made on samples having a moisture content of 50% to 65% (Epstein 1997). A compost stability respiration test was performed on the pre-composted raw feedstock, as well as the finished compost of each treatment form the final experimental run. The analysis was performed by Norwest Laboratories, using carbon dioxide evolution as a means of measuring respiration, method S99 (Bartha and Palmer 1965). Table 7-8 indicates the results of this analysis. Respiration is expressed as mg CO_2-C per gram of compost-C per day. Table 7-9 relates the respiration rate to the stability of the compost. The level of respiratory activity indicates the microbial activity of the compost as organic carbon is transformed to CO_2. A high respiration rate represents greater microbial activity, while a low respiration rate represents lower microbial activity where the available carbon has been utilized. Therefore the finished

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compost from this study can be categorized as being stable, characterized as a cured compost, with minimal impact on soil dynamics. This method of categorizing compost according to its stability is advantageous with respect to simplicity and low cost. Disadvantages however, include the use of small, disturbed samples. The measurement indicates the state of stability if the compost is homogeneous, and represents the entire mixture. However, most composts are not uniform, even a single wood particle can offset the respiration results and skew the data (Epstein 1997).

Table 7-8: Compost Stability Analysis Results.

Sample	Raw Feedstock	C:N = 90:1	C:N = 50:1	C:N = 30:1	C:N = 20:1
Organic Matter (%)	62.2	61.9	63.5	64.9	48.0
Moisture Content (%)	66.5	66.7	68.0	68.9	67.0
Carbon Dioxide Evolution (mg CO_2-C per g organic-C per day)	>4.0	2.1	3.1	2.4	3.8

Table 7-9: Compost Stability Index Based on Carbon Dioxide Evolution and Oxygen Consumption (Epstein 1997).

Respiration Rate	Rating	Characteristics
0-2 (mg CO_2-C/g compost-C-day) or 0-0.5 (mg O_2/g VS-hr)	Very stable	Well cured; no malodours; earthy odour; no continued decomposition
2-5 (mg CO_2-C/g compost-C-day) or 0-0.5 (mg O_2/g VS-hr)	Stable	Cured compost; minimal impact on soil dynamics; limited odour potential
5-10 (mg CO_2-C/g compost-C-day) or 0-0.5 (mg O_2/g VS-hr)	Moderately stable	Uncured compost; some malodour potential; addition to soil may immobilize N; high phytotoxicity potential; not recommended for growing plants from seed
10-20 (mg CO_2-C/g compost-C-day) or 0-0.5 (mg O_2/g VS-hr)	Stable compost	Very immature compost; high malodour and phytotoxicity potential; not recommended for growing plants from seed
>20 (mg CO_2-C/g compost-C-day) or 0-0.5 (mg O_2/g VS-hr)	Very unstable compost	Extremely unstable material; very high malodour and phytotoxicity potential; not recommended for use

The CCME Guidelines for Compost Quality (1996) state that for compost to be considered mature, certain criteria must be met. At the present, there is no single test of compost maturity that is reliable and sufficient by itself. One criterion is that a compost must conform to the following conditions: the C:N ratio must be ≤ 25, and oxygen uptake must be <150 mg O_2/kg organic matter (volatile solids) per hour. In order to satisfy the C:N requirements, the treatment using an initial C:N ratio of 20:1 was the only treatment investigated which fulfill such requirements. All other treatments investigate had a final C:N ratio greater than 25:1 (Table 7-10). Therefore additional nitrogen supplementation would be required to meet the CCME criteria. The data shows no significant changes in

C:N ratio through composting, this indicates little or no ammonia volatilization and nitrogen leaching.

Table 7-10: C:N Ratios – each an average of 4 (Appendix D).

	Reactor	Run #1	Run #2	Run #3	Average	Std. Dev.
Prior to Composting	R1	105:1	113:1	103:1	107:1	5.3
	R2	55:1	58:1	53:1	55:1	2.5
	R3	28:1	31:1	28:1	29:1	1.7
	R4	19:1	16:1	18:1	18:1	1.5
After Composting	R1	97:1	110:1	93:1	100:1	8.9
	R2	44:1	49:1	45:1	46:1	2.6
	R3	28:1	31:1	27:1	29:1	2.1
	R4	21:1	20:1	17:1	19:1	2.1

The second criterion concerning oxygen uptake, can be correlated to Table 7-9, where the criterion for mature compost relates to the compost stability index rating of very stable. Therefore, although each treatment can be categorized as stable by the compost stability index, the very stable rating was not achieved. Consequently, the compost does not meet the stability criteria for mature compost as defined by the CCME guidelines. To meet this requirement, each treatment would require curing such that the oxygen uptake rate would be < 150 mg O_2 / kg VS per hour. Once the stability criterion is met, the treatment with a initial C:N ratio of 20:1 would meet both the final C:N requirement and the respiration requirement. The other three treatments require additional nitrogen supplementation in order to meet CCME guidelines for mature compost. Other acceptable criteria for CCME maturity include, the germination of cress seeds and radish seeds, and curing for a designated time, organic matter reduction, or until the compost will not reheat upon

standing to greater than 20°C above ambient temperature (Table 7-11). Figures 7-11 and

7-12 are photographs, which illustrate the appearance of the composting mixture prior to

composting and after composting.

Table 7-11: CCME Compost Quality Guidelines for Compost Maturity (CCME 1996).

Compost shall conform to One of the following	Two of the following three requirements shall be met	$C:N \leq 25$
		O_2 uptake shall be < 150 mg O_2 / kg VS per hour
		Germination of cress or radish seeds in compost shall be greater than 90% of the germination rate of the control sample, and plant growth rate of compost-soil mix shall not be less than 50% in comparison to plant growth of the control sample.
	Or	The compost must be cured for a minimum of 21 days and the compost will not reheat upon standing to greater than 20°C above ambient temperature.
	Or	The compost must be cured for a minimum of 21 days and the reduction of organic matter must be $> 60\%$ by weight.
	Or	If no other determination is made, then the compost must be cured for a six-month period. The state of the curing pile must be conductive to aerobic biological activity. The curing stage begins when the pathogen reduction is complete and the compost no longer reheats to thermophilic temperatures.
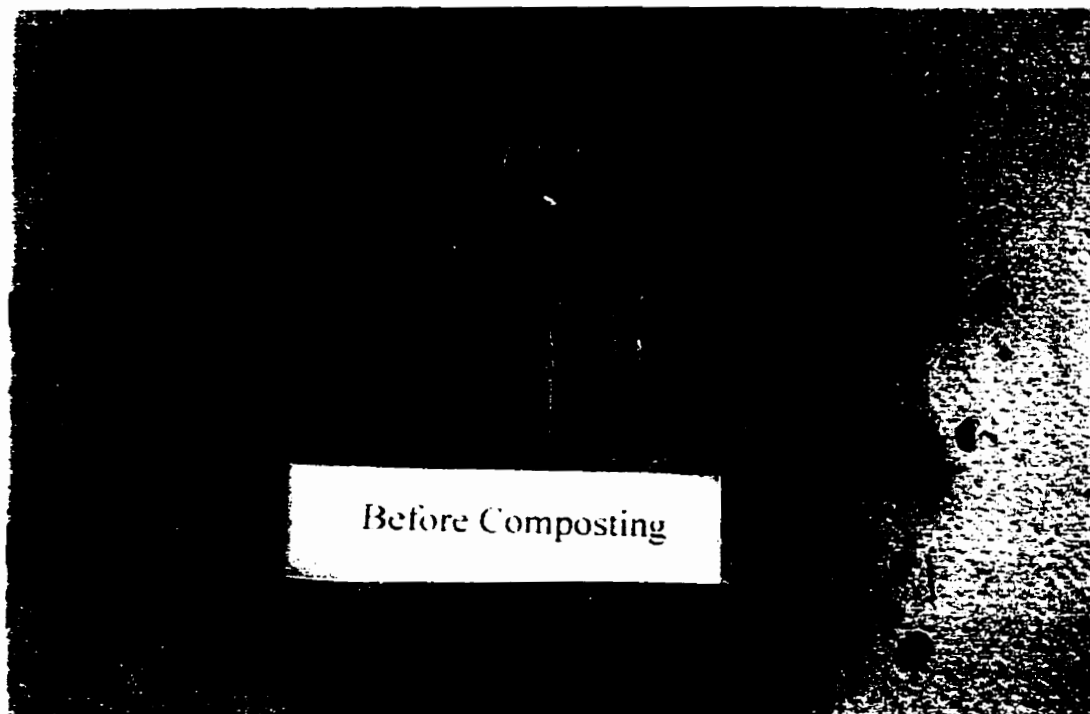
Figure 7-11: Pre-Composted Feedstock.
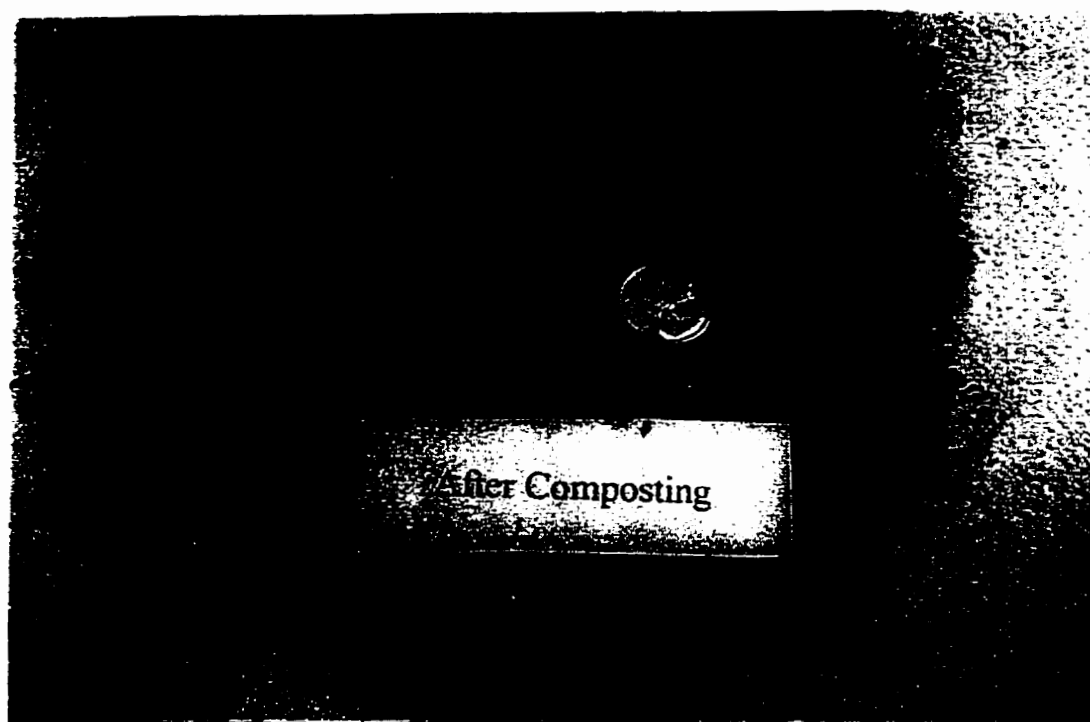
Figure 7-12: Composted Feedstock (C:N=20:1)

CHAPTER 8

SUMMARY AND CONCLUSIONS

The objective of this study was to identify and discuss alternatives for biosolids utilization at the Pine Falls Paper Company, and to examine further the option of composting through experimental work. Nutrient addition can represent a major cost of composting for a large-scale operation. This study examined the effects of nitrogen addition (C:N ratio) on the composting of PFPC's biosolids. Four bench-scale reactors were operated simultaneously, each with a different C:N ratio. Each treatment was run in triplicate in series. The reactors were designed to simulate core conditions of a large-scale windrow.

Based on the results of the experimental work of this investigation, the following conclusions can be made:

1. The preliminary feedstock characterization shows that the biosolids analyzed from the PFPC are within the range of typical values for a pulp and paper mill sludge for MC, VS, OC, TKN, and wet bulk density.

2. Compressive settlement causes FAS reduction within the composting matrix. This FAS reduction occurs relatively quickly, as approximately 75% of the total reduction occurred within the first half hour upon loading. Therefore, it is suggested that in a large-scale windrow, similar FAS reduction could be observed at the core. Turning of the windrow would temporarily increase the FAS within the windrow as well as aerate the pile. The FAS within the reactors remained

approximately between 20 and 35% throughout the duration of the experiment, this indicates that approximately 95% of the maximum oxygen consumption rate was maintained, according to Haug (1993).

3.   Upon completion of composting, treatment using C:N ratios ranging from 90:1 to 30:1 had odours which were pleasant to smell, with an increasingly sweet/earth odour as the C:N ratio was decreased. The treatment using a C:N ratio of 20:1 had a distinct strong ammonia smell. However, ammonia has a relatively high threshold odour concentration, dilutes rapidly to below detection, and is considered to be a relatively minor odourant for a composting facility.

4.   For each treatment investigated, composting mixtures reached thermophilic temperatures, peaked at approximately 8 days, and then declined. Treatments with decreasing C:N ratios, resulted in increased temperatures. In fact, as the C:N ratio decreased, the reactor temperature above chamber temperature increased linearly. Therefore, the heat output was correlated to C:N ratio. It is expected that there is an optimum C:N ratio value, beyond which point temperature begins to decrease. In conclusion, for the four C:N ratios investigated, heat output increased as the C:N ratio decreased from 90:1 to 20:1.

5.   The volatile solids destruction increased as the C:N ratio decreased. A linear correlation occurs between VS destruction and C:N ratios between 90:1 and 30:1. As the C:N ratio is decreased to 20:1, the rate at which VS destruction occurs

increased. The maximum VS destruction occurred using a C:N ratio of 20:1, this value was over 83% of the calculated theoretical value. It is expected that at lower C:N ratios, ammonia is given off and biological activity is impeded. The decreasing C:N ratio can therefore be correlated to the increase in VS destruction and temperature since heat output is a function of microbial activity.

6. Through composting the particle size distribution of the material shifted. Materials were divided into three categories: >1/4 inch (large); 1/8-1/4 inch (medium); and <1/8 inch (small). The large sized particles decreased in distribution by approximately 23%, the medium sized particles increased in distribution by approximately 14% and the small sized particles increased in distribution by approximately 9%. This shift towards a product with a smaller particle size distribution is beneficial for the final use of the compost, and helps minimize screening of the final product.

7. Each C:N ratio investigated in this study resulted in a finished product which can be categorized as being stable according to the compost stability index (Figure 7-9). This stable categorization is characterized as a cured compost, with minimal impact on soil dynamics and limited odour potential. This stability can be related to the CCME Compost Quality Guidelines for maturity. Though each of the C:N ratios investigated do not meet the stability requirements of "very stable", required for mature compost. This lack of stability was expected as the material had only undergone less than 18 days of composting with no curing. Nonetheless,

through proper curing, the stability rating of "very stable" is attainable. As well, in order for a compost to be considered mature, not only must the stability criterion be met, but also the final C:N ratio criterion (C:N≤25). Only the compost with an initial C:N ratio of 20:1, met the final C:N requirements as stipulated by CCME. Therefore, in order for the other three treatments investigated to meet CCME guidelines, addition nitrogen supplementation is required, and curing is required for each treatment.

CHAPTER 9

ENGINEERING SIGNIFICANCE AND RECOMMENDATIONS

Nitrogen fertilizer costs to bring the biosolids C:N ratio to 40:1, the top of the suggested reasonable range for composting and land application would be approximately $36,400 annually, delivered to Pine Falls (Even-Spray & Chemicals Ltd. 1998). The most likely source of composting amendment at the PFPC is bark, which is readily available on site. At a mixture of 0.75 kg bark/kg biosolids, a moisture content of 60% and a C:N ratio of 90% results. Therefore, the nitrogen addition costs to bring the C:N ratio of the mixture to 40:1, would be approximately $303,800 annually, delivered to Pine Falls (Even-Spray & Chemicals Ltd. 1998).

The optimum C:N ratio investigated (20:1), resulted in an increase in volatile solids reduction of 6% greater than the control (90:1), and showed similar temperature profiles. The results suggest that the added cost of nitrogen fertilizer may not be justified for increased composting performance. The marketability of compost may however require nitrogen addition in order to satisfy CCME requirements. In Canada, all compost produced for market should meet the CCME (Canadian Council of Ministers of the Environment) Guidelines for Compost Quality. One criterion of the CCME guidelines stipulates that the compost must be mature. Maturity can be measured by several parameters. Two such parameters include the stability of the compost as well as the final C:N ratio. The stability of the compost can be categorized as stable according to the compost stability index (Figure 7-9), but not to the extent required by the CCME guidelines. Therefore additional time is required to allow the compost to cure. Furthermore, the final C:N ratio must be ≤ 25 as stipulated by the CCME Guidelines.

Therefore fertilizer addition would be required for the marketability of the PFPC compost. In order to bring the C:N ratio from 90:1 to a suitable C:N ratio of 25:1, the cost would be approximately $628,200 annually delivered to Pine Falls (Even-Spray & Chemicals Ltd. 1998). These costs would account for the majority of the daily operating costs, and should be weighed against the potential revenue of the marketed compost product. Taking into account the cost considerations as well as the effect of the C:N ratio on composting performance, it may be argued that the CCME C:N ratio value of ≤ 25 should not be applied to Paper Mill composts.

Based on the results of this investigation, it is recommended that if the final compost is intended for market, and if CCME guidelines are to be met, the nitrogen fertilizer should be added prior to composting. This will provide a faster decomposition rate, a final product with a suitable C:N ratio and stability, and will eliminate the need for mixing after the composting process is complete. In other words, the nitrogen can be mixed during the initial mixing of biosolids and bark, thereby saving time and money at a later date. Suitable curing time is also required so that the respiration rate of the finished compost meets criteria outlined by the CCME Compost Quality Guidelines for compost maturity. It is also recommended that if CCME guidelines are to be met, just enough nitrogen be added to reduce the C:N ratio of the biosolids/bark mixture to a minimally acceptable C:N ratio of 25:1 as stipulated by the CCME Compost Quality Guidelines. This is due to the fact that reduction of the C:N ratio any further would provide minimal benefits with respect to decomposition rates but would consequently and substantially increase the cost due to further nitrogen requirements.

CHAPTER 10

SUGGESTIONS FOR FURTHER STUDY

Suggested further studies regarding the effect of C:N ratio on the composting performance of paper mill biosolids include:

1. Consider ammonia volatilization, ammonia volatilization will cause valuable nitrogen to be lost to the gaseous phase and cause potential odour problems. Monitoring the pH can provide an indication of ammonia volatilization, where a high pH favors the formation of ammonia gas, and a low pH maintains the nitrogen in the ammonium form. Another option is to use an acid trap, where ammonia can be quantified by back titration with a standardized solution. The final C:N ratio is proportional to the quantity of ammonia volatilized during composting.

2. Measure the oxygen uptake rate (OUR) as another means of determining the composting performance, however, this would require there be no forced aeration, thereby causing oxygen to be a limiting factor.

3. Repeat the experiment adding the nitrogen fertilizer in periodic intervals. Total nitrogen addition at the beginning of the experimental run may cause some toxic effects thereby retarding biological activity. Also, the sulfur coated urea used as fertilizer is a slow release fertilizer, therefore, all of the nitrogen may not have

been released during the composting period. Repeat the experiment using 46-0-0 urea to determine if the type of fertilizer used effects the composting process.

4. Repeat the experiment on a pilot scale to determine if similar results of this study occur. A field test would also provide valuable information such as volume reduction due to composting and large scale composting time requirements. Furthermore, include curing and conduct phytotoxicity tests, in order to determine the stability potential of the final product.

5. For each experimental run, use a different reactor for each C:N ratio investigated, this will eliminate bias results based on the reactor itself, rather than the actual C:N ratio under investigation.

Suggested further studies regarding the overall composting of PFPC biosolids include:

1. Sampling and laboratory analysis to fully characterize the biosolids. This data would be important for composting, land application, and waste to energy alternatives. The sampling and analysis plan suggested is outlined in Chapter 4 of this study. For composting, CCME Compost Quality Guidelines should be met and are based on criteria for product safety and quality, which include: foreign matter; maturity; pathogens; and trace elements.

2. Identifying potential markets. Suppliers should identify markets before initiating composting operations and adjust compost production accordingly to ensure the proper supply. Failure to identify and understand potential markets for compost can result in over- or under-production.

3. Investigating other parameters which may effect the composting performance of paper mill biosolids. Such parameters may include, moisture content, windrow size, turning frequency and composting time.

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APPENDIX A – RAW PRELIMINARY DATA

Sheet1

PRESS SOLIDS FROM JULY 1/96 TO PRESENT

Shift Report.Date	Cons - Pressed Sldge	Shift Report.Date	Cons - Pressed Sldge
01/07/96		25/07/96	25
01/07/96		25/07/96	26.5
02/07/96	24	26/07/96	25.4
02/07/96	22.91	26/07/96	26.71
03/07/96	26.5	27/07/96	25.99
03/07/96	26.48	27/07/96	27.25
04/07/96	24.7	28/07/96	26.14
04/07/96	23.6	28/07/96	25.9
05/07/96	25.2	29/07/96	25.4
05/07/96	25.7	29/07/96	26.3
06/07/96	28.75	30/07/96	29.2
06/07/96	25.07	30/07/96	25.6
07/07/96	28	31/07/96	26.5
07/07/96	26.2	31/07/96	25.8
08/07/96	24.3	01/08/96	
08/07/96	25.6	01/08/96	25.2
09/07/96	25.6	02/08/96	22.79
09/07/96	25.3	02/08/96	24.2
10/07/96	23.3	03/08/96	28.99
10/07/96	22.49	03/08/96	27.23
11/07/96	23.6	04/08/96	27.4
11/07/96	25	04/08/96	26.3
12/07/96	25.2	05/08/96	24.9
12/07/96	26	05/08/96	29.32
13/07/96	24	06/08/96	25.3
13/07/96	24.6	06/08/96	22.16
14/07/96	24.5	07/08/96	24.8
14/07/96	24.2	07/08/96	23.8
15/07/96	24.4	08/08/96	23.5
15/07/96	25.14	08/08/96	22.7
15/07/96	24.8	09/08/96	20.67
16/07/96	24.6	09/08/96	21.96
17/07/96	25.17	10/08/96	22.22
17/07/96	25.19	10/08/96	21.64
18/07/96	25.5	11/08/96	21.23
13/07/96	26.17	11/08/96	24.04
19/07/96	25.3	12/08/96	25.5
19/07/96	26.73	12/08/96	24.7
20/07/96	26.2	13/08/96	25.8
20/07/96	25.01	13/08/96	24.9
21/07/96	22.22	14/08/96	26.5
21/07/96	25.7	14/08/96	25.05
22/07/96	25.46	15/08/96	
22/07/96	27.29	15/08/96	26
23/07/96	25.6	16/08/96	20.5
23/07/96	23.3	16/08/96	24.55
24/07/96	23.9	17/08/96	23.06
24/07/96	24.5	17/08/96	22.3

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Date	Value	Date	Value
18/08/96	22.2	12/09/96	20.46
18/08/96	22.5	13/09/96	24.53
19/08/96	22.3	13/09/96	24.25
19/08/96	24.1	14/09/96	22.1
20/08/96	22.4	14/09/96	24.62
20/08/96	23.97	15/09/96	27.9
21/08/96	23	15/09/96	28.49
21/08/96	24.33	16/09/96	27.1
22/08/96	28.6	16/09/96	28.21
22/08/96	27.5	17/09/96	31.3
23/08/96	25.8	17/09/96	24.9
23/08/96	28.44	18/09/96	30.3
24/08/96	29.5	18/09/96	27.98
24/08/96	23.4	19/09/96	29.15
25/08/96	25	19/09/96	18.52
25/08/96	27	20/09/96	28.36
26/08/96	25.4	20/09/96	29.23
26/08/96	25	21/09/96	26.57
27/08/96	27.3	21/09/96	27.5
27/08/96	25.775	22/09/96	23.99
28/08/96	26.3	22/09/96	28.2
28/08/96	27.52	23/09/96	24.02
29/08/96	30	23/09/96	25.6
29/08/96	29.9	24/09/96	25.7
30/08/96	27.3	24/09/96	26.46
30/08/96	30.1	25/09/96	26.3
31/08/96	28.6	25/09/96	26.85
31/08/96	27.9	26/09/96	23.03
01/09/96	29.1	26/09/96	27.5
01/09/96	27.9	27/09/96	27.52
02/09/96		27/09/96	28.4
02/09/96		28/09/96	24.69
03/09/96	26.3	28/09/96	26.18
03/09/96	29.1	29/09/96	25.42
04/09/96	25.77	29/09/96	20.94
04/09/96	25.2	30/09/96	21.36
05/09/96	26.78	30/09/96	25.77
05/09/96	24.51	01/10/96	25.1
06/09/96	28.1	01/10/96	27.91
06/09/96	26.37	02/10/96	28.47
07/09/96	29.09	02/10/96	28.7
07/09/96	28.58	03/10/96	26.14
08/09/96	26.1	03/10/96	25.51
08/09/96	25.6	04/10/96	27.43
09/09/96	26.8	04/10/96	28.3
09/09/96	23.6	05/10/96	31.07
10/09/96	16.74	05/10/96	29.3
10/09/96	20.7	06/10/96	27.72
11/09/96	14.2	06/10/96	23.53
11/09/96	20.4	07/10/96	25.55
12/09/96	24.19	07/10/96	28.6

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08/10/96	26.6	02/11/96	25.35
08/10/96	27.7	03/11/96	24
09/10/96	29.2	03/11/96	28.6
09/10/96	24.6	04/11/96	27.6
10/10/96	29	04/11/96	27.5
10/10/96	26.1	05/11/96	24.11
11/10/96	28.2	05/11/96	26.3
11/10/96	28.6	06/11/96	25.84
12/10/96	29.4	06/11/96	24.3
12/10/96	28.67	07/11/96	34.7
13/10/96	26.2	07/11/96	30.4
13/10/96	24.6	08/11/96	27.33
14/10/96	27.77	08/11/96	24.28
14/10/96	26.65	09/11/96	25.28
15/10/96	25	09/11/96	28.9
15/10/96	27.57	10/11/96	30
16/10/96	26.6	10/11/96	30.57
16/10/96	30.9	11/11/96	30.6
17/10/96	24.5	11/11/96	28.5
17/10/96	27	12/11/96	29.1
18/10/96	30.3	12/11/96	30.56
18/10/96	31.2	13/11/96	27.4
19/10/96	28.42	13/11/96	28.7
19/10/96	30.7	14/11/96	25
20/10/96	23.79	14/11/96	31.8
20/10/96	28.91	15/11/96	30.71
21/10/96	23.6	15/11/96	29.41
21/10/96	26.83	16/11/96	29.01
22/10/96	28.09	16/11/96	30.64
22/10/96	25.2	17/11/96	29.9
23/10/96	20.8	17/11/96	21
23/10/96	26.64	18/11/96	20.7
24/10/96	24.6	18/11/96	28.1
24/10/96	27.1	19/11/96	31.4
25/10/96	26.5	19/11/96	27
25/10/96	30.53	20/11/96	23.2
26/10/96	36.37	20/11/96	28.5
26/10/96	34.4	21/11/96	27.25
27/10/96	31.4	21/11/96	28
27/10/96	28.5	22/11/96	28.01
28/10/96	23.61	22/11/96	34.6
28/10/96	26.59	23/11/96	27.3
29/10/96	21	23/11/96	29.18
29/10/96	25.43	24/11/96	28.2
30/10/96	29.5	24/11/96	30.05
30/10/96	32.27	25/11/96	25.5
31/10/96	23	25/11/96	26.3
31/10/96	23.49	26/11/96	26.8
01/11/96	27.3	26/11/96	
01/11/96	28.3	27/11/96	32.3
02/11/96	30.4	27/11/96	27.4

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Date	Value	Date	Value
28/11/96	25.8	23/12/96	30.3
28/11/96	21.3	24/12/96	22.2
29/11/96	22.33	24/12/96	17.53
29/11/96	20.5	25/12/96	
30/11/96	16	25/12/96	
30/11/96	16.5	26/12/96	
01/12/96	16.6	26/12/96	
01/12/96	25.62	27/12/96	
02/12/96	26.3	27/12/96	
02/12/96	23.32	28/12/96	
03/12/96	22.19	28/12/96	25.3
03/12/96	26.3	29/12/96	27.1
04/12/96	29.14	29/12/96	31.95
04/12/96	30.77	30/12/96	30.57
05/12/96	32.28	30/12/96	31.93
05/12/96	29.17	31/12/96	26.36
06/12/96	25.2	31/12/96	28.7
06/12/96	27.45	01/01/97	30.29
07/12/96	20.83	01/01/97	30.1
07/12/96	25.7	02/01/97	27.43
08/12/96	26.23	02/01/97	29.82
08/12/96	27.2	02/01/97	29.15
09/12/96	19.33	03/01/97	30
09/12/96	22.6	04/01/97	31.8
10/12/96	23.8	04/01/97	31.57
10/12/96	21.79	05/01/97	30.1
11/12/96	20.4	05/01/97	30.78
11/12/96	26.7	06/01/97	30
12/12/96	23.42	06/01/97	29.67
12/12/96	25.6	07/01/97	29.35
13/12/96	22.8	07/01/97	29.2
13/12/96	27.3	08/01/97	32.74
14/12/96	26.9	08/01/97	24.8
14/12/96	28.87	09/01/97	
15/12/96	30.33	09/01/97	20.38
15/12/96	31.2	10/01/97	25.27
16/12/96	25.78	10/01/97	29.5
16/12/96	30.4	11/01/97	25.72
17/12/96	26.27	11/01/97	29.03
17/12/96	32.35	12/01/97	29.7
18/12/96	25.42	12/01/97	26.9
18/12/96	33.2	13/01/97	22.5
19/12/96	27.71	13/01/97	28.56
19/12/96	29.33	14/01/97	29.3
20/12/96	29.63	14/01/97	20.03
20/12/96	31.58	15/01/97	26.75
21/12/96	31.3	15/01/97	28.2
21/12/96	29.8	16/01/97	
22/12/96	31.4	16/01/97	30.35
22/12/96	30.95	17/01/97	27.37
22/12/96	31.14	17/01/97	29.77

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Date	Value	Date	Value
18/01/97	22.21	12/02/97	29.7
18/01/97	31.37	13/02/97	15.73
19/01/97	31.7	13/02/97	29.5
19/01/97	28.25	14/02/97	27.2
20/01/97	27.1	14/02/97	27.76
20/01/97	29.25	15/02/97	28.3
21/01/97	30.09	15/02/97	27.54
21/01/97	26.03	16/02/97	29.9
22/01/97	29.08	16/02/97	26.53
22/01/97	28.2	17/02/97	24.94
23/01/97	30.75	17/02/97	28.3
23/01/97	20.08	18/02/97	29.9
24/01/97	27.72	18/02/97	28.92
24/01/97	27.97	19/02/97	21.7
25/01/97	28.37	19/02/97	33.33
25/01/97	28.29	20/02/97	28.3
26/01/97	26.9	20/02/97	28.5
26/01/97	27.18	21/02/97	26.05
27/01/97	24.55	21/02/97	25.3
27/01/97	24.57	22/02/97	22.96
28/01/97	22.2	22/02/97	29.9
28/01/97	25.5	23/02/97	31.9
29/01/97	26.99	23/02/97	30.37
29/01/97	25.34	24/02/97	30.04
30/01/97	26.5	24/02/97	29.7
30/01/97	27.4	25/02/97	29.3
31/01/97	29.48	25/02/97	32.01
31/01/97	30.34	26/02/97	29.08
01/02/97	27.04	26/02/97	29.59
01/02/97	28.5	27/02/97	28.
02/02/97	27.94	27/02/97	23.5
02/02/97	28.89	28/02/97	29.37
03/02/97	26.74	28/02/97	24.64
03/02/97	26.7	01/03/97	24.4
04/02/97	20.39	01/03/97	28.07
04/02/97	30.57	02/03/97	22.22
05/02/97	26.48	02/03/97	25.88
05/02/97	19.44	03/03/97	24.7
06/02/97	29.9	03/03/97	12.12
06/02/97	30.2	04/03/97	22.84
07/02/97	30.4	04/03/97	22
07/02/97	29.44	05/03/97	19.48
08/02/97	34.8	05/03/97	26.76
08/02/97	31.6	06/03/97	22.8
09/02/97	29.35	06/03/97	25.86
09/02/97	29.31	07/03/97	28.33
10/02/97	28.26	07/03/97	28.4
10/02/97	26.65	08/03/97	25.2
11/02/97	21.3	08/03/97	23.98
11/02/97	25.7	09/03/97	24.04
12/02/97	27.2	09/03/97	24.55

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Date	Value	Date	Value
10/03/97	25.6	04/04/97	31.1
10/03/97	23.33	05/04/97	30.9
11/03/97	24.01	05/04/97	24.94
11/03/97	24.64	06/04/97	23.28
12/03/97	23.98	06/04/97	31.8
12/03/97	26.1	07/04/97	28.6
13/03/97	26.1	07/04/97	33.18
13/03/97	22.7	08/04/97	28.69
14/03/97	25.5	08/04/97	27.5
14/03/97	24.91	09/04/97	28.1
15/03/97	22.79	09/04/97	27.17
15/03/97	25.12	10/04/97	28.09
16/03/97	23.7	10/04/97	27.2
16/03/97	23.4	11/04/97	26.5
17/03/97	22.7	11/04/97	30.7
17/03/97	23.3	12/04/97	33.4
18/03/97		12/04/97	34.1
18/03/97	23.8	13/04/97	25.5
19/03/97	26.17	13/04/97	33.7
19/03/97	30.67	14/04/97	22.5
20/03/97	29.41	14/04/97	33
20/03/97	30.14	15/04/97	27.1
21/03/97	28.2	15/04/97	33.34
21/03/97	21.8	16/04/97	32.2
22/03/97	30.15	16/04/97	34.9
22/03/97	35.77	17/04/97	33.3
23/03/97	35.61	17/04/97	30.02
23/03/97	27.9	18/04/97	32.4
24/03/97	33.17	18/04/97	31.1
24/03/97	33.54	19/04/97	32.28
25/03/97	31.5	19/04/97	32
25/03/97	35.58	20/04/97	31.5
26/03/97	23.54	20/04/97	31.5
26/03/97	26.69	21/04/97	30.5
27/03/97	36.08	21/04/97	31.6
27/03/97	37.44	22/04/97	30
28/03/97	39.12	22/04/97	28.5
28/03/97	36.8	23/04/97	30.17
29/03/97	35.8	23/04/97	30.28
29/03/97	32.7	24/04/97	28.6
30/03/97	37.49	24/04/97	23.04
30/03/97	37.24	25/04/97	27.5
31/03/97	34.01	25/04/97	24.53
31/03/97	31.2	26/04/97	27.46
01/04/97	37.1	26/04/97	27.2
01/04/97	33.58	27/04/97	26.8
02/04/97	33.3	27/04/97	29.4
02/04/97	32.65	28/04/97	27.2
03/04/97	31.2	29/04/97	29.25
03/04/97	26.33	29/04/97	25.13
04/04/97	32	29/04/97	30.69

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Date	Value	Date	Value
30/04/97	30	25/05/97	27.5
30/04/97	29.2	26/05/97	32.
01/05/97	29.7	26/05/97	28.69
01/05/97	29.94	27/05/97	33.49
02/05/97	31.19	27/05/97	37.4
02/05/97	30.9	28/05/97	31.5
03/05/97	33.9	28/05/97	31.5
03/05/97	24	29/05/97	30.2
04/05/97	34.8	29/05/97	30.6
04/05/97	26.14	30/05/97	32
05/05/97	33.2	30/05/97	38.7
05/05/97	38.4	31/05/97	31.7
06/05/97	31.6	31/05/97	30.2
06/05/97	35.9	01/06/97	28.49
07/05/97	36.9	01/06/97	36
07/05/97	32.69	02/06/97	34.84
08/05/97	37.5	02/06/97	35.13
08/05/97	29.96	03/06/97	34.9
09/05/97	37.21	03/06/97	30.63
09/05/97	31.2	04/06/97	30.5
10/05/97	30.5	04/06/97	27.96
10/05/97	29.8	05/06/97	32.1
11/05/97	33.87	05/06/97	34.3
11/05/97	37.56	06/06/97	25.4
12/05/97	32.17	06/06/97	34.76
12/05/97	31.9	07/06/97	33.1
13/05/97	33	07/06/97	32.1
13/05/97	29.33	08/06/97	35.2
14/05/97	26.4	08/06/97	37.3
14/05/97	28.97	09/06/97	36.2
15/05/97	28.47	09/06/97	33.9
15/05/97	28.97	10/06/97	30.6
16/05/97	21.36	10/06/97	32.05
16/05/97	27.1	11/06/97	
17/05/97	30.24	11/06/97	27
17/05/97	24.2	12/06/97	29.3
18/05/97	29.2	12/06/97	34.2
18/05/97	28.1	13/05/97	35.2
19/05/97	28.52	13/06/97	35.35
19/05/97	29.46	14/06/97	31.8
20/05/97	30.8	14/06/97	33.63
20/05/97	29.5	15/06/97	25.1
21/05/97	23.1	15/06/97	25.76
21/05/97	27.72	16/06/97	26.67
22/05/97	30.7	16/06/97	30.5
22/05/97	31.5	17/06/97	28.7
23/05/97	30.9	17/06/97	29.5
23/05/97	30.6	18/06/97	31.3
24/05/97	29.5	18/06/97	30.37
24/05/97	30.75	19/06/97	
25/05/97	31	19/06/97	31.7

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20/06/97	29.5		15/07/97	35.01
20/06/97	37.42		16/07/97	31.8
21/06/97	38.9		16/07/97	28.44
21/06/97	35.8		17/07/97	33.5
22/06/97	36.8		17/07/97	22.5
22/06/97	32.5		18/07/97	28.4
23/06/97	32.3		18/07/97	28
23/06/97	35.9		19/07/97	27.3
24/06/97	28.17		19/07/97	30.1
24/06/97	29.4		20/07/97	31.3
25/06/97	30.6		20/07/97	31.01
25/06/97	31.61		21/07/97	31.7
26/06/97	31.02		21/07/97	23.9
26/06/97	33.52		22/07/97	36.33
27/06/97	31.5		22/07/97	26.8
27/06/97	29.5		23/07/97	29.55
28/06/97	29.66		23/07/97	29.5
28/06/97	31.05		24/07/97	34.1
29/06/97	32.23		24/07/97	27.3
29/06/97	30.7		25/07/97	29.5
30/06/97	27.7		25/07/97	29.6
30/06/97	31		26/07/97	27.2
01/07/97	28.8		26/07/97	29.3
01/07/97	25.42		27/07/97	27.4
02/07/97	28.34	27/07/97	27.95
02/07/97	26			
03/07/97	32			
03/07/97	30.9			
04/07/97	25.63			
04/07/97	33			
05/07/97	29.61			
05/07/97	34.2			
06/07/97	29.7			
06/07/97	27.14			
07/07/97	31.7			
07/07/97	29.8			
08/07/97	28.2			
08/07/97	32.6			
09/07/97	33.1			
09/07/97	32.1			
10/07/97	30.4			
10/07/97	36.5			
11/07/97	30.4			
11/07/97	30.1			
12/07/97	28.97			
12/07/97	29			
13/07/97	30.58			
13/07/97	26.4			
14/07/97	28.39			
14/07/97	29.36			
15/07/97	24.95			

141
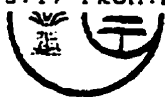
LABS

EDMONTON
CALGARY
LANGLEY
LETHBRIDGE
WINNIPEG

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P.O. NO

W.O. NO. 9 16920

PAGE   1

Pine Falls Paper Co.
Box 10, Hwy.11 & Mill Rd.
Pine Falls, Mb.
ROE 1MO

C. Laberniara
2043678351

29-07-96   Jul 29/96

SOILS AND FEED ANALYSIS REPORT

SAMPLE		14000 Sample 6	14001 Sample 7
ORGANIC MATTER			
TOT ORG CARBON	%	45.8 45.8	48.5 48.5
ORGANIC MATT %	%	83.3 93.3	56.3 86.3
C:N RATIO		16.5 16.5	15.1 15.1
NITROGEN	%	2.84 2.84	3.20 3.20
PG FERTILITY M.K			
AMMONIUM	ug/gm	1340 1340	810 810
NITRATE-N	ug/gm	<1.0 <1.0	<1.0 <1.0

LABS

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PAGE	1

NORWEST LABS-MANITOBA
AGRICULTURAL SERVICES
203, 545 UNIVERSITY CRES
WINNIPEG, MB
R3T 5S5

PINE FALLS PAPER

SAMPLE		1	2
		14030 SAMPLE 5	14031 SAMPLE 7
PHYSICAL			
MOIST.WET WT.	%	0.1	0.1
TRACE ICP 3051			
ALUMINUM	ug/gm	1230	1340 1460
ARSENIC	ug/gm	<1.0	<1.0
ANTIMONY	ug/gm	<0.25	<0.25
BARIUM	ug/gm	50.9	51.0
BERYLLIUM	ug/gm	0.128	0.127
BISMUTH	ug/gm	<0.35	<0.35
CADMIUM	ug/gm	1.56	1.77
CALCIUM	ug/gm	9400	9980 9980
CHROMIUM	ug/gm	12.3	12.1
COBALT	ug/gm	0.680	0.635
COPPER	ug/gm	10.5	16.6
IRON	ug/gm	1470	1460
LEAD	ug/gm	2.9	3.1
MAGNESIUM	ug/gm	1090	1040 1040
MANGANESE	ug/gm	115	123
MOLYBDENUM	ug/gm	1.79 1.79	1.34 1.29
NICKEL	ug/gm	4.95 4.99	3.95
PHOSPHORUS	ug/gm	3680	3590
SELENIUM	ug/gm	1.60	0.99
SILVER	ug/gm	0.192	0.215
SILICON	ug/gm	229 229	235
STRONTIUM	ug/gm	13.6	13.4
THALLIUM	ug/gm	<0.20	<0.20
TITANIUM	ug/gm	43.6 43.5	42.5
TIN	ug/gm	0.36	0.37
VANADIUM	ug/gm	5.63 5.59	5.56
ZINC	ug/gm	66.3	71.2 71.2

Lab Manager: _____

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NORWEST LABS

Robert Sopuck

WO (Lang.) : 22053
PO #   :
Date Rec'd. : 11/15/96
Date Comp. : 11/21/96

Client		Received From	
Name	: PINE FALLS PAPER CO. LTD.	Name	:
Address	: P.O. Box 10, Hwy 10 & Mill Rd. Pine Falls, MB R0E 1M0	Address	:
Phone	: (204) 367-5244	Phone	:
Fax	: (204) 367-8797	Fax	:
Attn.	: Leon Hanlan	Attn.	:
Project	:		

RESULTS OF ANALYSIS

Lab #:   22053-1
Sample ID: Press Sludge Sample
                                                     Rec'd Nov. 14/96

Parameter:

C:N Ratio		24.56
Organic Matter	(%)	74.8
Total Organic Carbon	(%)	42.0
Total Kjeldahl Nitrogen	(%)	1.71

Approved: _____
Randy Neumann, B.Sc.
Laboratory Manager

Accredited By: CANADIAN ASSOCIATIO   TORIES (CAEAL)
            For specifi

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TABLE 1: Heavy metal content of six Pine Falls Paper Co. (biosolid) samples collected at the company's Waste Water Treatment Plant from May-July 1996. June 6 sample analyzed by Enviro-test labs, Edmonton; all others by Norwest labs, Winnipeg

[handwritten above columns: May 24 '96, May 27 '96, June 6 '96, July 4 '96, July 9 '96, July 11 '96, July 16 '96, July 18 '96, July 23 '96]

Element	5/24/96	5/27/96	6/6/95	7/4/96	7/9/96	7/11/96	7/16/96	7/18/96	7/23/96	7/26/96	7/30/96
ALUMINUM	1590	1600	2470	2420	1730	2110	3100	1830			
ANTIMONY	<0.38	<0.35		2.0	<1.0	<1.0	1.5	<1.0			
ARSENIC	<0.75	<0.70		<0.25	<0.25	<0.25	<0.25	<0.25			
BARIUM	132	72.6	71.8	107	78.1	78.3	102	74.0			
BERYLLIUM	0.117	0.175	<1	0.156	0.109	0.121	0.174	0.130			
BISMUTH	<0.53	<0.49		<0.35	0.62	0.38	0.86	0.42			
CADMIUM	1.11	1.85	0.9	1.44	2.03	1.99	2.13	1.99			
CALCIUM	9070	11700		11300	11100	10700	15900	12100			
CHROMIUM	8.75	12.7	1.25	15.5	13.8	15.2	22.8	20.0			
COBALT	0.721	0.951	<1	0.944	0.841	0.69	1.28	0.788			
COPPER	12.8	14.8	14	16.6	12.4	13.2	15.9	13.7			
IRON	1980	2150		2470	1830	1960	3180	1950			
LEAD	3.8	2.8	<5	5.8	3.8	3.9	4.7	3.8			
MAGNESIUM	1090	1720		1520	1360	1410	2110	1530			
MANGANESE	207	228		247	231	214	234	180			
MOLYBDENUM	1.19	1.74	2	1.42	1.34	1.52	1.67	1.86			
NICKEL	8.02	8.99	7	7.09	5.85	6.95	8.82	6.62			
PHOSPHORUS	4840	9910		5140	5840	6110	7580	7330			
SELENIUM	<0.23	0.74		1.92	1.82	1.17	1.93	3.47			
SILICON	215	266		341	138	160	415	890			

TABLE 1 cont'd

	May 24	May 27	June 26	July 4	July 7	July 11	June	July 14			
SILVER	0.211	0.251		0.086	0.118	0.089	0.103	0.132			
STRONTIUM	21.9	14	17	23	15.5	15.3	21.6	16.7			
THALLIUM	<0.30	<0.28	<1	<0.20	<0.20	<0.20	<0.20	<0.20			
TIN	<0.23	<0.21	<5	63.4	63.5	71.4	82.7	72.1			
TITANIUM	18.1	18.7		0.72	0.43	0.5	0.90	2.82			
VANADIUM	8.49	8.27	8	9.25	7.89	8.17	11.3	8.13			
ZINC	49.2	80.9	78.5	71.5	74.0	74.3	92.5	82.9			

' All values are measured in parts per million (ppm)

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TABLE 2. Organic material content of Pine Falls Paper Company biosolid samples taken from the Waste Water Treatment Plant. Tests done by Norwest Labs. Winnipeg.

Totals and %	5/10/96	5/24/96	5/27/96	7/4/96	7/10/96	7/11/96	7/16/96	7/18/96
Total Organic Carbon	53.8%	55.9%	54.4%	48.1%	51.9%	51.4%	52.6%	53.4%
Organic Matter %	95%	99.5%	99.5%		92.4%	91.5%	93.6%	95.1%
C:N Ratio	18.4	22.9	22.9		16.0	14.6	15.3	16.5
Nitrogen %	2.90%	2.44%	4.93%		3.24%	3.53%	3.43%	3.23%
Nitrate-N	<1.0	<1.0	<1.0		12.5	<1.0		
Ammonium	<1.0	630	1450		352	840		

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APPENDIX B – ENERGY FROM WASTE CALCULATIONS

Preliminary Calculations

Estimation of Chemical Composition

Ultimate analysis values estimated from (Scott and Smith 1995).

Component	% at 42% solids
Carbon	31.1
Hydrogen	4.4
Oxygen	30.1
Nitrogen	0.9
Sulfur	0.2
Ash	14.0

Compute the molar composition of the elements neglecting ash
Assume a total of 100 grams of biosolids

Component	At. Wt. (gm/mol)	Moles
Carbon	12.01	2.59
Hydrogen	1.01	4.36
Oxygen	16.00	1.88
Nitrogen	14.01	0.06
sulfur	32.07	0.01

Determine the normalized mole ratios

Component	Mole Ratio (S=1)
Carbon	415.2
Hydrogen	698.6
Oxygen	301.7
Nitrogen	10.3
sulfur	1.0

Write chemical formula with sulfur at 42% solids content
$C_{415}H_{699}O_{302}N_{10}S$

Energy Content Estimation

Value for waste used in Scott & Smith 1995 given as
12.2 MJ/kg (5245 BTU/lb)

Using the modified Dulong formula

$Btu/lb = 145C + 610(H_2 - 0.125\ O_2) + 40S + 10N$

where C= carbon, % by weight

H_2 = hydrogen, % by weight

O_2 = oxygen, % by weight

S = sulfur, % by weight

N = nitrogen, % by weight

Determine the % distribution by weight

Component	# atoms/mole	At. Wt.	Weight	%
Carbon	415	12	4982.73	46.64
Hydrogen	699	1	698.55	6.54
Oxygen	302	16	4826.54	45.18
Nitrogen	10	14	144.21	1.35
sulfur	1	32	32.00	0.30
Total			10684.0342	100.00

Btu/lb = 145(46.6) + 610(6.5 - (45.2/8)) + 40(0.3) + 10(1.3)
Energy Content = 7301 Btu/lb
Energy Content = 17.0 MJ/kg

Estimate the Volume Reduction and Volume of Residue After Combustion

Assume that the specific weight of the residue is 600 kg/m^3

Assume that the specific weight of the biosolids is 220 kg/m^3

Using the data from Scott and Smith 1995,

% Inert Residue (Ash) = 14 %

Estimate original and final volumes before and after combustion
for the combustion of 1000 kg of biosolids

Original Volume = 1000kg/220kg/m^3 = 4.55 m^3

Residue Volume = (14% * 1000 kg)/600 kg/m^3 = 0.23 m^3

Estimate the volume reduction

Volume Reduction = ((4.55-0.23)/4.55) * 100 = 95%

Estimate the Effects of Excess Air on Temperature and Composition of Flue Gases

Assume: all of the carbon initially present is converted to CO_2

The energy content of the biosolids is 12.2MJ/kg as determined

Computation Table

Component	Weight, %	At. Wt.	At. Wt. Units	Moles O$_2$ req.	Reaction
Carbon	31.1	12.0	2.592	2.592	C+O₂=CO₂
Hydrogen	4.4	1.0	4.400	1.1	2H₂+O₂=2H₂O
Oxygen	30.1	16.0	1.881	-0.941	
Nitrogen	0.9	14.0	0.064		
sulfur	0.2	32.1	0.006	0.006	S+O₂=SO₂
Water	19.3	18.0	1.072		
Ash	14.0				
Total	100.0			2.757	

Moles of air required per 100 lbs of biosolids = 2.757/0.2069 = 13.33

Lbs of air required per pound of biosolids = 13.33(28.7)/100 = 3.83

Assumed air composition in volume fractions: CO2=0.0003, N2=0.7802, O2=0.2069, H2O=0.0126

Assuming ideal gases, the volume fractions may be taken as mole fractions. In the air composition just given

it is assumed that rare gases are included with the nitrogen and that the air moisture content is at 70% relative

humidity at 60deg F. Air of this composition has a weight of 28.7 lb/mol

Determine moles of flue gases produced by the stoichiometric
combustion of 100 lbs of biosolids

Moles of Flue Gases

Product	From Combustion	From Air	Total	%
CO_2	2.592	0.004	2.596	15.76
H_2O	3.272	0.168	3.44	20.88
O_2				
N_2	0.032	10.400	10.432	63.32
SO_2	0.006		0.006	0.04
Total			16.474	100.00

Moles of air per mole of flue gas = 13.33/16.474 = 0.81

Computation table to determine flue gas composition for various quantities
of excess air assuming 100 moles of flue gas from stoichiometric
combustion.

% excess air, (moles excess)	Total moles of gas	Gas Composition, percent				
		CO_2	O_2	N_2	H_2O	SO_2
0 (0.0)	100.0	15.8	0.0	63.3	20.88	<0.1
50 (40.5)	140.5	11.2	6.0	67.6	15.2	<0.1
100 (81.0)	181.0	8.7	9.3	69.9	12.1	<0.1

Determine the enthalpy of the flue gas for the two percentages of excess air at 1000, 1500, 2000, & 2500 °F
Using the following table:

Temp (°F)	Btu/lb * mol over standard state[a]			
	CO_2	O_2	N_2	H_2O
1000	10048	6974	6720	26925
1500	16214	11008	10556	31743
2000	22719	15191	14520	36903
2500	29539	19571	18609	42405

[a]Gas, except liquid water, at 1 atm pressure, and 77°F

Btu in product gas/lb of solid waste = [(moles of flue gas/lb of solid waste)*(total moles of gas/
moles of flue gas)]*[Sum(mole fraction of gas component)(Btu/moles of gas component)]

For 1000°F and 50 % excess air
Btu in flue gas/lb of solid waste = (.1647 moles of flue gas/lb solid waste)(140.5/100)*
[.112(10048 Btu/mole)+0.06(6974 Btu/mole)+.676(6720 Btu/mole)+.152(26925)]
=2355 Btu/lb solid waste

Summary Table

Temp. °F	Btu in flue gas/lb solid waste	
	Excess Air 50%	Excess Air 100%
1000	2355	2825
1500	3341	4070
2000	4369	5367
2500	5439	6714

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Determine the temperature of the flue gas at 50 and 100% excess air

Assume energy content is 5245 Btu/lb (Scott & Smith 1995) and that 15% of the energy is lost then 4458 Btu/lb of biosolids must remain in the flue gas

By interpolation from the previous summary table, the flue gas temp. is about 2040 °F at 50% excess air and about 1645 °F at 100% excess air.

This technique used to estimate the effects of heat losses and various amounts of excess air on combustion is not entirely accurate.

Estimate Materials Heat Balance - detetmine the heat available from the combustion of 200 tonnes/day of biosolids with the following characteristics

Use 33% water, 14% non-combustible and estimates of elements

Component	% of total	kg/day	lb/day
Combustible	53.0	106000	233690
Noncombistible	14.0	28000	61729
Water	33.0	66000	145505

Element	%
Carbon	24.7
Hydrogen	3.5
Oxygen	23.9
Nitrogen	0.7
Sulfur	0.2
Water	33.0
Inerts	14.0

Assume the following:

The as fired heating value of the waste is 5245 btu/lb (12.2 MJ/kg)

The grate residue contains 5% unburned carbon

Temperatures: entering air=80°F, grate residue=800°F

Specific heat of residue = 0.25 Btu/lb-°F

Latent heat of water = 1040 Btu/lb

Radiation Loss = 0.005 Btu/Btu of gross heat input

All oxygen in waste is bound as water

Theoretical air requirements based on stoichiometry

Carbon:	$C + O_2 \rightarrow CO_2$	= 11.52 lb/lb
Hydrogen:	$2H_2 + O_2 \rightarrow 2H_2O$	= 34.56 lb/lb
Sulfur:	$S + O_2 \rightarrow SO_2$	= 4.31 lb/lb

The net hydrogen available for combustion is equal to percent hydrogen minus 1/8 of the percent oxygen. This accounts for the bound water in the dry combustible material.

The heating value of carbon is 14000 Btu/lb

Moisture in the combustion air is 1%

Computation Table

Element	lb/d
Carbon	108908
Hydrogen	15432
Oxygen	105381
Nitrogen	3086
Sulfur	882
Water	145505
Inerts	61729
Total	440924

Comput the amount of residue
Inerts = 61729 lb/d
Total Residue = 61729/0.95 = 64978 lb/d
Carbon in Residue = 64978 - 61729 = 3249 lb/d

Determine the amount of Hydrogen and bound water
Net available hydrogen, % = (3.5% - 23.9/8) =0.513% = 2262 lb/d
Hydrogen in bound water = (3.5% - 0.513%) = 2.987% = 13170 lb/d
Bound water = oxygen + hydrogen in bound water = 105381 + 13170 = 118551 lb/d

Computation table -required air

Element	Calculation	Air req (lb/d)
Carbon	=(108908-3249)(11.52)	1217192
Hydrogen	=2262(34.56)	787174
Sulfur	=882(4.31)	3801
Total dry theoretical air	=3.83(from earlier calc)*440924	1688739
Total dry air inc. 100 % excess		3696906
Moisture	=1688739(0.01)	16887
Total		3713793

Determine the amount of water produced from the combustion of available hydrogen:
H_2O = 18 lb H_2O / 2 lb H * (2262 lb/d) = 20358 lb/d

Prepare a heat balance for the combustion process

Item	10^6 Btu/d

Gross heat input
    440924 lb/d * (5245 Btu/lb)   2312.6
Heat loss in unburned carbon
    3249 lb/d * (14000 Btu/d)   -45.5
Radiation Loss
    0.005 Btu/Btu * (2312.6 X 10^6 Btu/d)   -11.6
Inherent moisture
    145505 lb/d * (1040 Btu/d)   -151.3
Moisture in bound water
    118551 lb/d * (1040 Btu/d)   -123.3
Moisture from the combustion of available oxygen
    20358 lb/d * (1040 Btu/d)   -21.2
Sensible heat in residue

64978 lb/d [0.25 Btu/lb-°F(800-80)°F]   -11.7
Total losses
                                                                        -364.6
Net heat available in flue gases
                (2312.6-364.6) X 10^6 Btu/d   1948.0
Combustion Efficiency
                (1948 X 10^6 Btu/d/2312.6 X 10^6 Btu/d) * 100%   84.2%

If the boiler efficiency were 85%, then the overall combustion efficiency
would be 84.2% * 85%, which would be about 71.6%. This value is consistent
with values obtained in modern MSW combustion systems (Tchobanoglous et al. 1993)

APPENDIX C – COMPOSTING AREA CALCULATIONS

Spreadsheet used to calculate composting recipes using two starting materials.

a. Enter material characteristics in table.

Material	%MC	%N (dry wt.)	C:N wt.:wt.	Bulk Density kg/m3
Wet (b)	66.58	0.87	47.9	440
Dry (a)	51.21	0.21	257.5	200

To determine the required recipe:

a. Enter target moisture content below.

b. Record the target moisture content, the amount of amendment, & the resulting C:N ratio.

Enter the target moisture content =	60 %
The required amount of amendment =	0.749 kg per kg of material b.
The resulting C:N Ratio =	91.65 of mixture.

To determine the resulting volume of material to be composted:

a. Enter the amount of material composted annually.

b. Enter the expected volume reduction when materials are mixed. This is typically a 20% volume reduction so the default value is 0.8.

c. Record the amount of material composted annually, the expected volume reduction, the resulting start-up volume, & the resulting weight..

Enter the amount of material b which is composted annually =	72000 tonnes / year
Enter the amount of volume reduction expected (default = 0.8) =	0.8
The resulting volume of mixture at start-up is =	346500 cubic metres per year
The resulting weight of material at start-up is =	125898 tonnes / year
The resulting bulk density at start-up is =	363 kg / cubic metre

To determine the volume of material on the composting pad:

a. Enter the material retention time (MRT) for the composting operation

b. Enter a windrow shrinkage factor, typically a 25% volume reduction so default value is 0.75.

c. Record the MRT, the shrinkage factor, & the material volume.

Enter the MRT =	60 days
Enter the shrinkage factor =	0.75
The resulting material volume of the composting pad is =	42719.12 cubic metres

To determine the number of windrows required:

a. Enter the length of windrow that the site allows. This is usually controlled by the existing site conditions.

b. Assuming a bucket loader is used for the turning, enter the target pile height. Normal pile heights range from 1.8 m (6 feet) to 3.6 m (12 feet).

c. Record the length, height base width, & the required number of windrows.

Enter the windrow length =	50 Metres

Enter the target pile height =   3.6 Metres
The resulting pile base width is =   6.00 Metres
The resulting number of windrows are =   59.3 Windrows

To determine the composting area requirements:

a.   Enter the space required between each windrow. Typically, 6 metres (20 feet) are required between each
b.   windrow to allow for movement of the bucket loader.
c.   Enter the space required between the windrows and the edge of the composting pad. Typically, 3 metres
d.   (10 feet) are required between the windrows and the edge of the pad.
c.   Record the spaces used and the composting pad dimensions.

Enter the space between each windrow =   6 metres
Enter the space between the windrows and the edge of the pad =   3 metres
The required pad dimensions are =   720 metres by   56 metres.
The required area for composting is =   40320   Square metres.

To determine the curing area requirements:

a. Enter the MRT in the curing stage.

b. Enter the shrinkage factor. Typically, the material shrinks about 50% from the volume at the time of
start-up, so the default value is 0.5.
c. Enter the average depth of the curing piles. Typically, an average depth of 1.2 metres (4 feet) is expected.

d. Enter the space required between the curing piles and the edge of the curing pad.

e. Enter the width of the curing pad. Typically this is 1.5 metres (5 feet) less than one half of the windrow length.

e.   Record the MRT, the shrinkage facto¬, the average depth, the space used, the width of the curing pad,
and the curing pad dimensions.

Enter the MRT =   30 days
Enter the shrinkage factor =   0.5
Enter the average curing pile depth =   1.2 m
Enter the space required between the piles and the edge of the pad =   3 m
The width of the curing pad as a function of the windrow length =   23.5 m
The amount of material in the curing area s =   14239.7 m3
The required pad dimensions are =   511.0 by 28 m
The required area for curing is =   14307 m2

To determine the required compost storage area:

a. Enter the MRT in the storage area.

b. Enter the average depth of the storage piles. Typically, 2.5 metres (8 feet).

c. Enter the space required between the storage piles and the edge of the pad.

d. Enter the width of the storage pad. Typically, this is 1.5 metres (5 feet) less than one half of the windrow length.

e. Record . . .

Enter the MRT =   180 days
Enter the average storage pile depth =   2.5 metres
Enter the space required between piles and edge of pad =   3 metres.
The width of the storage pad as a function of the windrow length =   23.5 metres
The amount of material in the storage area =   85438.2 cubic metres
The required pad dimensions are =   1460.3 By 28 m
The required area for storage is =   40888 square metres.

To determine the overall pad dimensions:

Sum the requirements for composting, curing, and storage.

The total area required is =   95514 M2 or 23.6 acres

The total area required per unit weight of wet feedstock =   1.33 m2
                                                                   per year
                                                                   per tonne

APPENDIX D – EXPERIMENTAL LABORATORY DATA

Kevin Larsen Thesis Composting Experiment

Run #0

74.5% Primary, 6.5% Secondary, 19% Dip

Material collected December 15, 1997

Feedstock Characterization

Solids Data					Date: January 8, 1998					
Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (% wb)	% VS (% db)	% FS (% db)	% OC$^\wedge$ (% db)
Biosolids	J-3	86.12	127.84	99.46	88.61	33.54	66.46	74.25	25.75	41.25
Biosolids	27	96.60	137.03	110.26	99.86	33.46	66.54	76.37	23.63	42.43
Biosolids	51	80.96	122.89	94.98	84.35	33.44	66.56	75.82	24.18	42.12
Biosolids	57	91.59	137.68	106.92	96.60	33.26	66.74	73.84	26.16	41.02
Biosolids Mean						33.42	66.58	76.07	24.83	41.71
Biosolids Std. Dev.						0.12	0.12	1.22	1.22	0.66
Bark	45	83.17	105.32	94.09	83.56	49.30	50.70	96.43	3.57	53.57
Bark	2	91.84	111.62	101.22	92.10	47.42	52.58	97.23	2.77	54.02
Bark	74	85.54	109.23	97.09	86.00	48.75	51.25	96.02	3.98	53.34
Bark	7	89.28	113.46	101.29	89.69	48.79	50.33	96.59	3.41	53.66
Bark Mean						48.79	51.21	96.57	3.43	53.65
Bark Std. Deviation						0.96	0.96	0.50	0.50	0.28

$^\wedge$ OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

TKN Prepared Samples Solids Data					Date: January 15, 1998					
Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (% wb)	% VS (% db)	% FS (% db)	% OC$^\wedge$ (% db)
Biosolids	7	89.28	96.08	95.84	90.82	96.47	3.53	75.00	25.00	41.67
Biosolids	J-3	85.12	90.82	90.61	86.47	96.32	3.68	75.41	24.59	41.89
Biosolids	51	80.95	89.08	88.78	82.89	96.31	3.69	75.22	24.78	41.79
Biosolids	2	91.84	100.43	100.14	93.87	96.62	3.38	75.54	24.46	41.97
Biosolids Mean						96.43	3.57	75.29	24.71	41.83
Biosolids Std. Dev.						0.15	0.15	0.24	0.24	0.13
Bark	J-15	71.60	79.22	78.91	71.83	95.93	4.07	96.85	3.15	53.81
Bark	45	83.16	93.03	92.63	83.47	95.95	4.05	96.73	3.27	53.74
Bark	27	96.80	107.78	107.33	97.12	95.90	4.10	96.96	3.04	53.87
Bark	74	85.52	94.58	94.21	85.81	95.92	4.08	96.66	3.34	53.70
Bark Mean						95.92	4.08	96.80	3.20	53.78
Bark Std. Deviation						0.02	0.02	0.13	0.13	0.07

$^\wedge$ OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #0 DATA

Sample	Sample Weight (g)	Analyser Reading	Concentration of N (mg/L)	Result (mg/kg)	% N (%+F119wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
TKN Data	Date: January 21, 1998								
Blank	50 mL	0.659							
Blank	50 mL	0.717							
Blank Mean		**0.688**							
Standard	25 mL	18.02	97.13						
Standard	25 mL	18.36	99.03						
Standard Mean			**98.08**						
Biosolids	0.1	6.365		7953	0.81				
Biosolids	0.1	6.334		7910	0.81				
Biosolids	0.1	6.725		8458	0.86				
Biosolids	0.1	6.967		8797	0.90				
Biosolids Mean					**0.84**	**96.43**	**0.87**	**41.83**	**47.9**
Biosolids Std. Dev.					0.04				
Bark	0.5	7.46		1898	0.19				
Bark	0.5	7.906		2022	0.21				
Bark	0.5	8.273		2125	0.22				
Bark	0.5	7.233		1834	0.19				
Bark Mean					**0.20**	**95.92**	**0.21**	**53.78**	**257.4**
Bark Std. Deviation					0.01				

RUN #0 DATA

Particle Density - Pycronometer Method | Date: January 14, 1998

Temperature = 20°C, Density of H$_2$O (@20°C) = 0.998 g/cm^3

Feedstock Type	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H$_2$O (g)	Tare + H$_2$O (g)	Dry Particle Density (g/cm^3)
Biosolids	7	77.94	97.44	221.59	218.42	1.94
Biosolids	R3	78.71	96.80	225.76	222.69	2.03
Biosolids	35	78.11	91.00	221.25	219.29	1.83
Biosolids	R4	75.97	89.02	219.57	217.41	1.98
Biosolids Mean						1.94
Biosolids Std. Dev.						0.07
Bark	C	76.00	83.40	218.91	220.28	0.72
Bark	9	66.75	74.82	213.11	214.37	0.76
Bark	O	76.03	84.72	217.76	218.81	0.80
Bark	5	78.36	89.11	219.58	221.14	0.77
Bark Mean						0.76
Bark Std. Deviation						0.03

Bulk Density - Core Method | Date: January 16, 1998

Feedstock Type	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm^3)	Dry Volume (cm^3)	Wet Bulk Density (g/cm^3)	Dry Bulk Density (g/cm^3)	Dry Particle Density (g/cm^3)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
Biosolids	B1	172.45	271.36	206.19	225	200	0.44	0.17	1.94	0.91	0.11	0.80
Biosolids	C1	173.21	276.09	208.18	230	205	0.45	0.17	2.03	0.92	0.11	0.80
Biosolids	A2	172.09	265.27	203.71	210	190	0.44	0.17	1.83	0.91	0.11	0.80
Biosolids	10	174.92	270.47	207.11	225	200	0.42	0.16	1.98	0.92	0.11	0.81
Biosolids Mean							0.44	0.17	1.94	0.91	0.11	0.80
Biosolids Std. Dev.							0.01	0.00	0.07	0.00	0.00	0.01
Bark	B2	173.40	220.41	196.60	235	200	0.20	0.12	0.72	0.94	0.06	0.88
Bark	9	140.43	195.27	168.03	275	240	0.20	0.12	0.76	0.84	0.06	0.78
Bark	R2	169.67	221.98	195.36	275	240	0.19	0.11	0.80	0.85	0.05	0.79
Bark	J-7	171.53	226.90	199.49	275	240	0.20	0.12	0.77	0.87	0.06	0.81
Bark Mean							0.20	0.11	0.76	0.87	0.06	0.82
Bark Std. Deviation							0.01	0.00	0.03	0.05	0.00	0.05

RUN #0 DATA

Particle Density - Pycronometer Method				Date: January 20, 1998		
Temperature = 20+A54°C, Density of H_2O (@20°C) = 0.998 g/cm^3						
Feedstock Type	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H_2O (g)	Tare + H_2O (g)	Dry Particle Density (g/cm^3)
Biosolids	R3	80.95	99.82	227.27	225.31	1.45
Biosolids	R4	78.10	94.35	220.83	218.50	1.75
Biosolids	K	80.25	96.81	224.71	223.15	1.39
Biosolids	O	78.20	98.24	221.93	219.25	1.66
Biosolids Mean						1.56
Biosolids Std. Dev.						0.15
Bark	14	66.24	74.35	212.48	212.70	0.95
Bark	9	68.92	78.03	217.01	217.50	0.90
Bark	35	80.12	88.35	220.77	221.35	0.87
Bark	Z	80.47	89.13	220.22	221.24	0.80
Bark Mean						0.88
Bark Std. Deviation						0.05

Bulk Density - Core Method				Date: January 20, 1998	
Feedstock Type	Beaker #	Tare (g)	Tare + Feedstock (g)	Wet Volume (cm^3)	Wet Bulk Density (g/cm^3)
Biosolids	20	534.6	1215.1	1500	0.45
Biosolids	C3	542.0	1141.1	1400	0.43
Biosolids Mean					0.44
Biosolids Std. Dev.					0.02
Bark	A4	545.3	902.8	1700	0.21
Bark	X	504.0	852.2	1800	0.19
Bark Mean					0.20
Bark Std. Deviation					0.01

Calculations for Required Fertilizer Addition for Desired Initial C:N Ratios for 0.75 kg bark / kg biosolids (using feedstock characterization data)						
Desired C:N Ratio	%N of Fertilizer	%N of Sludge/ Bark Mixture	% Carbon	% Fertilizer Required	Weight of Compost (g)	Weight of Fertilizer Required (g)
91:1	32	0.53	47.96	0.00	726.41	0.00
50:1	32	0.53	47.96	0.54	726.41	3.93
30:1	32	0.53	47.96	1.34	726.41	9.73
20:1	32	0.53	47.96	2.34	726.41	16.99

RUN #0 DATA

Preliminary Compost Characterization

0.75 kg of bark / kg of biosolids

Solids Data										Date: January 21, 1998
Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%+K157db)
Compost	J-3	85.12	107.84	94.68	86.27	42.08	57.92	87.97	12.03	48.87
Compost	46	83.18	108.09	93.56	84.56	41.67	58.33	86.71	13.29	48.17
Compost	7	89.29	111.46	98.49	90.54	41.50	58.50	86.41	13.59	48.01
Compost	74	85.53	106.07	94.06	86.65	41.53	58.47	86.87	13.13	48.26
Compost Mean						41.69	58.31	86.99	13.01	48.33
Composts Std. Dev.						0.27	0.27	0.68	0.68	0.38

^ OC (Organic Carbon) calculated using the following equation: $OC = (1-FS)/1.8$ (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

TKN Prepared Samples Solids Data										Date: January 27, 1998
Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
Compost	J-15	71.62	78.93	78.64	72.50	96.03	3.97	87.46	12.54	48.59
Compost	2	91.85	101.69	101.28	93.05	95.83	4.17	87.27	12.73	48.49
Compost	27	96.81	106.48	106.08	97.98	95.86	4.14	87.38	12.62	48.54
Compost	51	80.97	91.52	91.07	82.27	95.73	4.27	87.13	12.87	48.40
Compost Mean						95.87	4.13	87.31	12.69	48.51
Compost Std. Dev.						0.12	0.12	0.14	0.14	0.08

^ OC (Organic Carbon) calculated using the following equation: $OC = (1-FS)/1.8$ (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

TKN Data										Date: January 28, 1998
Sample	Sample Weight (g)	Analyser Reading	Concentration of N (mg/L)	Result (mg/kg)	% N (%wb)	% TS (%wb)	% N (%db)	% C (%+I185db)	C/N	
Blank	50 mL	0.806								
Blank	50 mL	0.759								
Blank Mean		0.783								
Standard	25 mL	18.93	101.70							
Standard	25 mL	18.49	99.23							
Standard Mean			100.47							
Compost	0.3	10.14		4370	0.43					
Compost	0.3	10.52		4547	0.45					
Compost	0.3	10.21		4403	0.44					
Compost	0.3	9.691		4160	0.41					

Compost Mean					0.43	95.87	0.45	48.51	107.1
Compost Std. Dev.					0.02				

Particle Density - Pycronometer Method — Date: January 21, 1998

Temperature = 20°C, Density of H_2O (@20°C) = 0.998 g/cm³

Feedstock Type	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H_2O (g)	Tare + H_2O (g)	Dry Particle Density (g/cm³)
Compost	T	189.57	217.09	492.34	492.96	0.99
Compost	C01	120.74	140.18	373.22	372.96	1.01
Compost	341	128.62	148.89	375.78	374.98	1.02
Compost	gp6	102.57	114.04	227.01	225.94	1.05
Compost Mean						1.02
Compost Std. Dev.						0.02

Bulk Density - Core Method — Date: January 21, 1998

Feedstock Type	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
Compost	B2	173.39	233.31	197.37	190	175	0.32	0.14	0.99	0.86	0.08	0.78
Compost	10	174.91	225.94	195.91	160	155	0.32	0.14	1.01	0.87	0.08	0.79
Compost	blank	167.25	222.69	190.13	170	150	0.33	0.15	1.02	0.85	0.09	0.76
Compost	J-7	171.52	229.44	195.66	185	170	0.31	0.14	1.05	0.86	0.08	0.78
Compost Mean							0.32	0.14	1.02	0.86	0.08	0.78
Compost Std. Dev.							0.01	0.01	0.02	0.01	0.00	0.01

Physical Analysis for Loading Effect on FAS of Composting Mixture — Date: January 21, 1998

	No Loading				12 kg Loading After 30 Minutes			
Weight of Compost (kg)	Height (cm)	Volume (cm³)	Wet Bulk Density (g/cm³)	FAS (cm³/cm³)	Height (cm)	Volume (cm³)	Wet Bulk Density (g/cm³)	FAS (cm³/cm³)
0.73	25.0	2248	0.32	0.78	15.5	1394	0.52	0.40

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RUN #0 DATA

Bark for Run #4, collected March 26, 1997

Feedstock Characterization

Solids Data Date: April 2, 1998

Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^Y (%+K223db)
Bark	45	83.18	99.63	91.00	83.40	47.54	52.46	97.19	2.81	53.99
Bark	25	92.16	112.21	101.64	92.53	47.28	52.72	96.10	3.90	53.39
Bark	30	94.17	116.23	104.33	94.41	46.06	53.94	97.64	2.36	54.24
Bark	3	90.94	109.43	99.40	91.18	45.75	54.25	97.16	2.84	53.98
Bark Mean						46.66	53.34	97.02	2.98	53.90
Bark Std. Deviation						0.88	0.88	0.65	0.65	0.36

Y OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

Solids Data Using Moisture Balance Mar. 29, 1998

	% TS (%wb)	% MC (%wb)
Sample 1	48.5	51.5
Sample 2	47.4	52.6
Sample 3	50.5	49.5
Mean	48.8	51.2

TKN Prepared Samples Solids Data Date: April 6, 1998

Feedstock Type	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^Y (%+K241db)
Bark	11	81.61	91.46	90.96	81.91	94.92	5.08	96.79	3.21	53.77
Bark	25	92.16	100.90	100.46	92.41	94.97	5.03	96.99	3.01	53.88
Bark	4	91.91	102.29	101.76	92.22	94.89	5.11	96.86	3.15	53.81
Bark	1	90.37	100.14	99.64	90.67	94.88	5.12	96.76	3.24	53.76
Bark Mean						94.92	5.08	96.86	3.16	53.80
Bark Std. Deviation						0.04	0.04	0.10	0.10	0.06

Y OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #0 DATA

TKN Data — Date: April 8, 1998

Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N H2O (%wb)	% TS (%wb)	% N (%db)	% C (%+H2774 p)	C/N
Blank		5						
Blank		5						
Blank Mean		5.000						
Standard		10	5.00					
Standard		16.5	10.00					
Standard		35.5	25.00					
Standard		68.5	50.00					
Standard		94.00	70.00					
Bark	0.3	21	14.5	0.24				
Bark	0.3	22	15	0.25				
Bark	0.3	18	12	0.20				
Bark	0.3	17.5	11.5	0.19				
Bark Mean			0.22	94.92	0.23	53.80	231.86	
Bark Std. Deviation					#DIV/0!			

Particle Density - Pycronometer Method — Date: April 2, 1998

Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Feedstock Type	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
Bark	A	120.75	151.31	370.52	372.93	0.85
Bark	35	124.86	141.74	255.27	256.91	0.83
Bark	C	102.59	122.28	223.51	225.91	0.79
Bark	T	189.73	229.13	489.15	492.28	0.85
Bark Mean						0.83
Bark Std. Deviation						0.03

RUN #0 DATA

Bulk Density - Core Method		Date: April 2, 1998										
Feedstock Type	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
Bark	B2	173.43	236.41	201.50	315	255	0.20	0.11	0.85	0.87	0.06	0.81
Bark	1	170.21	234.70	199.66	300	245	0.21	0.12	0.83	0.85	0.06	0.79
Bark	R	166.27	236.48	198.52	350	285	0.20	0.11	0.79	0.86	0.06	0.80
Bark	K	165.11	237.36	199.22	355	295	0.20	0.12	0.85	0.86	0.06	0.80
Bark Mean							0.20	0.11	0.83	0.86	0.06	0.80
Bark Std. Deviation							0.01	0.00	0.03	0.01	0.00	0.01

RUN #1 DATA

Kevin Larsen Thesis Composting Experiment
Run #1
74.5% Primary, 6.5% Secondary, 19% Dip

Calculations for Required Fertilizer Addition for Desired Initial C:N Ratios for 0.75 kg bark / kg biosolids
(using feedstock characterization data)

Desired C:N Ratio	%N of Fertilizer	%N of Sludge/ Bark Mixture	% Carbon	% Fertilizer Required	Weight of Compost (g)	Weight of Fertilizer Required (g)
91:1	32	0.53	47.96	0	726.41	0
50:1	32	0.53	47.96	0.54	726.41	3.93
30:1	32	0.53	47.96	1.34	726.41	9.73
20:1	32	0.53	47.96	2.34	726.41	16.99

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RUN #1 DATA

Solids Data - precomposted									
Date: February 26, 1998									
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	51	80.97	91.54	85.12	81.52	39.26	60.74	86.75	13.25	48.19
R1	27	96.81	106.94	100.97	97.29	41.07	58.93	88.46	11.54	49.15
R1	1	90.36	100.71	94.39	90.90	38.94	61.06	86.60	13.40	48.11
R1	43	83.76	93.23	87.47	84.21	39.18	60.82	87.87	12.13	48.82
R1 Mean						39.61	60.39	87.42	12.58	48.57
R1 Std. Dev.						0.98	0.98	0.90	0.90	0.50
R2	J-15	71.62	82.27	75.80	72.21	39.25	60.75	85.89	14.11	47.71
R2	111	91.29	101.08	95.08	91.81	38.71	61.29	86.28	13.72	47.93
R2	11	81.60	90.91	85.21	82.08	38.78	61.22	86.70	13.30	48.17
R2	47	84.09	95.61	88.67	84.69	39.76	60.24	86.90	13.10	48.28
R2 Mean						39.12	60.88	86.44	13.56	48.02
R2 Std. Dev.						0.49	0.49	0.45	0.45	0.25
R3	17	86.86	96.44	90.81	87.32	41.23	58.77	88.35	11.65	49.09
R3	J-12	87.11	97.06	91.05	87.66	39.60	60.40	86.04	13.96	47.80
R3	7	85.70	95.55	89.54	86.20	38.98	61.02	86.98	13.02	48.32
R3	35	92.65	102.25	96.49	93.12	40.00	60.00	87.76	12.24	48.76
R3 Mean						39.95	60.05	87.28	12.72	48.49
R3 Std. Dev.						0.95	0.95	1.00	1.00	0.56
R4	118	103.91	113.10	107.85	104.33	42.87	57.13	89.34	10.66	49.63
R4	2	91.84	101.09	95.64	92.35	41.08	58.92	86.58	13.42	48.10
R4	23	90.54	101.23	94.87	91.18	40.51	59.49	85.22	14.78	47.34
R4	4	91.91	100.90	95.55	92.35	40.49	59.51	87.91	12.09	48.84
R4 Mean						41.24	58.76	87.26	12.74	48.48
R4 Std. Dev.						1.12	1.12	1.77	1.77	0.98

^ OC (Organic Carbon) calculated using the following equation OC = (1-FS)/1 8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #1 DATA

TKN Prepared Samples Solids Data - precomposted					Date: March 5, 1998					
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	2	91.84	96.03	95.80	92.31	94.51	5.49	88.13	11.87	48.96
R1	11	81.60	86.73	86.48	82.17	94.74	5.26	88.27	11.73	49.04
R1	23	90.53	96.11	95.81	91.15	94.62	5.38	88.26	11.74	49.03
R1	35	92.63	97.34	97.12	93.16	95.33	4.67	88.20	11.80	49.00
R1 Mean						94.80	5.20	88.21	11.79	49.01
R1 Std. Dev.						0.36	0.36	0.06	0.06	0.04
R2	4	91.90	97.20	96.92	92.50	94.72	5.28	88.05	11.95	48.92
R2	J-15	71.61	76.66	76.40	72.20	94.85	5.15	87.68	12.32	48.71
R2	118	103.89	108.67	108.42	104.44	94.77	5.23	87.86	12.14	48.81
R2	57	91.58	95.96	95.74	92.09	94.97	5.03	87.95	12.05	48.86
R2 Mean						94.83	5.17	87.89	12.11	48.83
R2 Std. Dev.						0.11	0.11	0.16	0.16	0.09
R3	47	84.06	89.06	88.83	84.64	95.38	4.62	88.21	11.79	49.01
R3	111	91.27	96.63	96.37	91.90	95.15	4.85	87.65	12.35	48.69
R3	1	90.35	95.27	95.02	90.92	94.92	5.08	87.79	12.21	48.77
R3	7	86.68	89.92	89.71	87.06	93.52	6.48	87.46	12.54	48.59
R3 Mean						94.74	5.26	87.78	12.22	48.77
R3 Std. Dev.						0.84	0.84	0.32	0.32	0.18
R4	J-12	87.09	93.06	92.75	87.80	94.81	5.19	87.46	12.54	48.59
R4	27	96.79	102.54	102.24	97.47	94.78	5.22	87.52	12.48	48.62
R4	51	80.95	85.92	85.66	81.54	94.77	5.23	87.47	12.53	48.60
R4	43	83.74	88.79	88.52	84.34	94.65	5.35	87.45	12.55	48.58
R4 Mean						94.75	5.25	87.47	12.53	48.60
R4 Std. Dev.						0.07	0.07	0.03	0.03	0.02

^ OC (Organic Carbon) calculated using the following equation OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #1 DATA

TKN Data - precomposted			Date: March 12, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (%+E251wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
Blank		5.5						
Blank		6.5						
Blank Mean		6.0						
Standard		10	5.00					
		15	10.00					
		37.5	25.00					
		65.5	50.00					
Standard		100.00	75.00					
R1	0.1	13.5	8.0	0.40				
R1	0.1	14.5	9.0	0.45				
R1	0.1	14.5	9.0	0.45				
R1	0.1	15.5	9.5	0.48				
R1 Mean				0.44	94.80	0.47	49.01	105.0
R1 Std. Dev.				0.03				
R2	0.1	27	18.0	0.90				
R2	0.1	26.5	17.8	0.89				
R2	0.1	23.5	15.5	0.78				
R2	0.1	24.5	16.3	0.82				
R2 Mean				0.85	94.83	0.89	48.83	54.9
R2 Std. Dev.				0.06				
R3	0.2	93	69.5	1.74				
R3	0.2	88	65.0	1.63				
R3	0.2	85	63.5	1.59				
R3	0.2	90	67.0	1.68				
R3 Mean				1.66	94.74	1.74	48.77	28.0
R3 Std. Dev.				0.06				
R4	0.1	74.5	55.0	2.75				
R4	0.1	57.5	42.0	2.10				
R4	0.1	64	47.0	2.35				
R4	0.1	70	51.5	2.58				
R4 Mean				2.44	94.75	2.57	48.60	18.9
R4 Std. Dev.				0.28				

RUN #1 DATA

Date: March 3, 1998

Particle Density - Pycronometer Method - precomposted
Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	C	102.58	113.35	225.49	225.79	0.93
R1	A	120.72	133.29	371.72	371.04	1.16
R1 Mean						1.04
R1 Std. Dev.						0.16
R2	B	107.59	117.77	247.43	247.42	1.00
R2	D	128.56	140.41	374.51	374.31	1.04
R2 Mean						1.02
R2 Std. Dev.						0.03
R3	A	120.73	130.20	372.74	372.77	0.99
R3	B	107.59	119.95	246.29	246.01	1.06
R3 Mean						1.02
R3 Std. Dev.						0.05
R4	D	128.58	141.73	373.61	373.63	0.99
R4	C	102.57	111.9	225.02	224.56	1.13
R4 Mean						1.06
R4 Std. Dev.						0.10

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RUN #1 DATA

Bulk Density - Core Method - precomposted							Date: March 6, 1998					
Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	D	168.21	221.69	190.42	165	145	0.32	0.15	0.93	0.84	0.09	0.74
R1	B	178.21	235.26	201.65	180	160	0.32	0.15	1.16	0.87	0.09	0.78
R1 Mean							0.32	0.15	1.04	0.86	0.09	0.76
R1 Std. Dev.							0.01	0.00	0.16	0.03	0.00	0.03
R2	K	171.76	215.62	189.02	140	110	0.31	0.16	1.00	0.84	0.10	0.75
R2	A	176.98	225.47	197.21	145	120	0.33	0.17	1.04	0.84	0.10	0.74
R2 Mean							0.32	0.16	1.02	0.84	0.10	0.74
R2 Std. Dev.							0.01	0.01	0.03	0.00	0.01	0.01
R3	10	174.90	215.69	191.32	130	105	0.31	0.16	0.99	0.84	0.09	0.75
R3	L	170.91	224.36	191.89	160	130	0.33	0.16	1.06	0.85	0.10	0.75
R3 Mean							0.32	0.16	1.02	0.84	0.10	0.75
R3 Std. Dev.							0.01	0.00	0.05	0.00	0.00	0.00
R4	F	171.64	217.89	190.99	155	130	0.30	0.15	0.99	0.85	0.09	0.76
R4	T	175.46	228.65	196.89	160	130	0.33	0.16	1.13	0.85	0.10	0.76
R4 Mean							0.32	0.16	1.06	0.85	0.09	0.76
R4 Std. Dev.							0.02	0.01	0.10	0.00	0.01	0.00

RUN #1 DATA

Run #2 started February 25, 1998 @ 3:00 pm
Reactors aerated at a flow rate of approximately 15mL/sec for 5 min every hour
At time zero, the thermostat on the chamber was set to an initial temp. of 35°C.

Compaction Data								
Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	R1 (cm)	R2 (cm)	R3 (cm)	R4 (cm)
February	25	15:00	0.0	0.00	25.0	25.0	25.0	25.0
	25	15:30	0.5	0.02	15.0	14.9	15.0	15.2
	25	16:00	1.0	0.04	14.7	14.6	14.8	15.0
	26	8:30	17.5	0.73	13.7	13.4	13.5	13.7
	26	15:30	24.5	1.02	13.2	13.1	13.0	13.2
	27	9:00	42.0	1.75	13.1	12.9	13.0	13.1
	27	16:00	49.0	2.04	13.0	12.9	12.9	13.0
	28	15:00	72.0	3.00	12.9	12.8	12.8	12.9
March	1	15:00	96.0	4.00	12.5	12.4	12.4	12.6
	2	11:30	116.5	4.85	12.2	12.1	12.1	12.2
	2	16:30	121.5	5.06	12.1	12.0	12.0	12.2
	3	10:00	139.0	5.79	12.1	11.9	11.9	12.1
	3	15:30	144.5	6.02	12.0	11.8	11.6	12.0
	4	10:30	163.5	6.81	12.0	11.6	11.5	11.9
	5	10:00	187.0	7.79	11.9	11.3	11.2	11.6
	5	15:30	192.5	8.02	11.8	11.3	11.2	11.4
	6	8:30	209.5	8.73	11.8	11.2	11.1	11.3
	6	16:00	217.0	9.04	11.6	11.1	11.0	11.2
	7	13:00	238.0	9.92	11.6	11.1	11.0	11.1
	8	14:00	263.0	10.96	11.5	11.1	11.0	11.1
	9	11:30	284.5	11.85	11.4	11.1	11.0	11.1
	9	16:00	289.0	12.04	11.3	11.0	10.8	11.0
	10	9:00	306.0	12.75	11.3	11.0	10.7	11.0
	10	15:30	312.5	13.02	11.3	10.9	10.5	10.9
	11	11:30	332.5	13.85	11.3	10.9	10.5	10.9
	11	15:30	336.5	14.02	11.2	10.9	10.4	10.8
	12	8:30	353.5	14.73	11.2	10.9	10.4	10.8
	12	15:00	360.0	15.00	11.2	10.9	10.4	10.8
	13	9:00	378.0	15.75	11.2	10.9	10.4	10.8
	13	14:00	383.0	15.96		10.9	10.4	10.8
	14	13:00	406.0	16.92			10.4	10.8

RUN #1 DATA

Temperature Data

Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	Chamber (°C)	R1 (°C)	R2 (°C)	R3 (°C)	R4 (°C)
February	25	15:00	0.0	0.00	24.0	24.0	24.0	24.0	24.0
	26	8:30	17.5	0.73	34.8	35.1	35.1	35.5	35.3
	26	15:30	24.5	1.02	35.3	35.8	36.0	36.8	36.3
	27	9:00	42.0	1.75	35.7	36.2	37.1	38.9	38.6
	27	16:00	49.0	2.04	36.3	36.8	37.8	39.8	39.6
	28	15:00	72.0	3.00	37.0	40.3	40.6	41.5	40.8
March	1	15:00	96.0	4.00	41.2	43.6	44.6	43.6	42.5
	2	11:30	116.5	4.85	44.1	45.1	47.0	46.4	44.9
	2	16:30	121.5	5.06	45.1	45.6	47.6	47.2	45.6
	3	10:00	139.0	5.79	45.8	46.6	48.8	49.4	48.1
	3	15:30	144.5	6.02	46.5	46.9	49.0	49.6	48.4
	4	10:30	163.5	6.81	47.1	47.5	49.5	50.4	50.2
	5	10:00	187.0	7.79	47.8	48.5	50.3	51.7	51.7
	5	15:30	192.5	8.02	48.8	48.9	50.4	51.8	51.9
	6	8:30	209.5	8.73	46.9	47.7	49.0	50.8	50.9
	6	16:00	217.0	9.04	46.1	46.7	47.9	48.5	49.7
	7	13:00	238.0	9.92	44.9	45.3	46.6	47.6	48.2
	8	14:00	263.0	10.96	44.3	45.0	46.1	47.3	48.0
	9	11:30	284.5	11.85	43.1	43.5	44.6	45.5	45.7
	9	16:00	289.0	12.04	41.7	42.1	43.3	44.2	44.5
	10	9:00	306.0	12.75	40.8	41.4	42.2	43.1	43.6
	10	15:30	312.5	13.02	39.7	40.1	41.0	41.7	42.1
	11	11:30	332.5	13.85	37.2	37.6	38.8	39.2	38.6
	11	15:30	336.5	14.02	37.0	37.3	38.3	38.9	39.3
	12	8:30	353.5	14.73	36.0	36.4	37.2	37.6	38.1
	12	15:00	360.0	15.00	35.4	35.6	36.4	37.0	37.2
	13	9:00	378.0	15.75	35.0	34.5	35.3	35.8	36.0
	13	14:00	383.0	15.96	35.0		34.9	35.4	35.6
	14	13:00	406.0	16.92	35.0			34.8	35.0

RUN #1 DATA

Physical Analysis for Loading Effect on FAS of Composting Mixture - 12 kg load				
Time (days)	R1 FAS (cm³/cm³)	R2 FAS (cm³/cm³)	R3 FAS (cm³/cm³)	R4 FAS (cm³/cm³)
0.00	0.76	0.74	0.75	0.76
0.02	0.38	0.34	0.38	0.35
0.04	0.37	0.32	0.37	0.34
0.73	0.33	0.28	0.32	0.29
1.02	0.31	0.26	0.30	0.27
1.75	0.30	0.26	0.30	0.26
2.04	0.30	0.26	0.30	0.26
3.00	0.30	0.25	0.29	0.26
4.00	0.28	0.24	0.28	0.24
4.85	0.27	0.22	0.26	0.23
5.06	0.26	0.22	0.26	0.23
5.79	0.26	0.22	0.26	0.22
6.02	0.26	0.21	0.24	0.22
6.81	0.26	0.20	0.24	0.22
7.79	0.26	0.19	0.23	0.20
8.02	0.25	0.19	0.23	0.20
8.73	0.25	0.19	0.22	0.19
9.04	0.24	0.18	0.22	0.19
9.92	0.24	0.18	0.22	0.18
10.96	0.24	0.18	0.22	0.18
11.85	0.24	0.18	0.22	0.18
12.04	0.23	0.18	0.21	0.18
12.75	0.23	0.18	0.21	0.18
13.02	0.23	0.18	0.20	0.18
13.85	0.23	0.18	0.20	0.18
14.02	0.23	0.18	0.20	0.17
14.73	0.23	0.18	0.20	0.17
15.00	0.23	0.18	0.20	0.17
15.75	0.23	0.18	0.20	0.17
15.96			0.20	0.17
16.92			0.20	0.17

RUN #1 DATA

Solids Data - composted										
Date: March 16, 1998										
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC* (%db)
R1	J-15	71.61	86.67	77.26	72.48	37.52	62.48	84.60	15.40	47.00
R1	4	91.89	116.81	101.30	93.31	37.76	62.24	84.91	15.09	47.17
R1	111	91.27	110.81	96.82	92.34	36.64	63.36	85.83	14.17	47.68
R1	35	92.62	115.29	101.37	93.84	36.60	63.40	84.91	15.09	47.17
R1 Mean						38.13	61.87	85.06	14.94	47.26
R1 Std. Dev.						0.57	0.57	0.53	0.53	0.29
R2	J-12	87.09	107.22	94.47	88.32	36.66	63.34	83.33	16.67	46.30
R2	51	80.95	103.65	89.31	82.24	36.83	63.17	84.57	15.43	46.98
R2	7	85.67	106.37	93.40	86.91	37.34	62.66	83.96	16.04	46.64
R2	118	103.88	125.96	112.06	105.12	37.05	62.95	84.84	15.16	47.13
R2 Mean						36.97	63.03	84.18	15.82	46.76
R2 Std. Dev.						0.29	0.29	0.67	0.67	0.37
R3	11	81.59	106.23	90.84	83.03	37.54	62.46	84.43	15.57	46.91
R3	57	91.57	109.79	98.31	92.63	36.99	63.01	84.27	15.73	46.82
R3	27	96.79	121.15	105.92	96.10	37.48	62.52	85.65	14.35	47.58
R3	47	84.07	108.72	93.18	85.42	36.96	63.04	85.18	14.82	47.32
R3 Mean						37.24	62.76	84.88	15.12	47.16
R3 Std. Dev.						0.31	0.31	0.65	0.65	0.36
R4	2	91.83	116.59	101.65	93.40	36.70	63.30	84.01	15.99	46.67
R4	43	83.74	109.22	93.15	85.26	36.83	63.07	83.85	16.15	46.56
R4	1	90.35	116.08	99.95	91.77	37.31	62.69	85.21	14.79	47.34
R4	23	90.52	117.10	100.43	82.06	37.28	62.72	84.26	15.74	46.81
R4 Mean						37.06	62.84	84.33	15.67	46.86
R4 Std. Dev.						0.30	0.30	0.61	0.61	0.34

* OC (Organic Carbon) calculated using the following equation OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #1 DATA

TKN Prepared Samples Solids Data - composted					Date: March 30, 1998					
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	2	91.86	98.50	98.06	92.70	93.37	6.63	86.45	13.55	48.03
R1	4	91.92	98.72	98.29	92.77	93.68	6.32	86.66	13.34	48.14
R1	51	80.98	87.44	87.03	81.80	93.65	6.35	86.45	13.55	48.03
R1	J-15	71.64	77.31	76.94	72.32	93.47	6.53	87.17	12.83	48.43
R1 Mean						93.54	6.46	86.68	13.32	48.16
R1 Std. Dev.						0.15	0.15	0.34	0.34	0.19
R2	43	83.77	91.27	90.75	84.75	93.07	6.93	85.96	14.04	47.76
R2	J-12	87.12	95.22	94.66	88.19	93.09	6.91	85.81	14.19	47.67
R2	47	84.10	92.78	92.18	85.25	93.09	6.91	85.77	14.23	47.65
R2	111	91.30	99.13	98.58	92.35	92.98	7.02	85.58	14.42	47.54
R2 Mean						93.05	6.95	85.78	14.22	47.65
R2 Std. Dev.						0.05	0.05	0.16	0.16	0.09
R3	23	90.56	98.03	97.52	91.56	93.17	6.83	85.63	14.37	47.57
R3	118	103.92	110.78	110.31	104.80	93.15	6.85	86.23	13.77	47.90
R3	11	81.62	88.7	88.21	82.52	93.08	6.92	86.34	13.66	47.97
R3	57	91.60	98.57	98.09	92.50	93.11	6.89	86.13	13.87	47.85
R3 Mean						93.13	6.87	86.08	13.92	47.82
R3 Std. Dev.						0.04	0.04	0.31	0.31	0.17
R4	2	85.71	94.23	93.68	86.83	93.54	6.46	85.95	14.05	47.75
R4	27	96.82	105.31	104.76	97.92	93.52	6.48	86.15	13.85	47.86
R4	35	92.65	99.36	98.92	93.52	93.44	6.56	86.12	13.88	47.85
R4	1	90.37	99.33	98.76	91.54	93.64	6.36	86.05	13.95	47.81
R4 Mean						93.54	6.46	86.07	13.93	47.82
R4 Std. Dev.						0.08	0.08	0.09	0.09	0.05

^ OC (Organic Carbon) calculated using the following equation OC = (1-FS)/1 8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #1 DATA

TKN Data - composted			Date: March 25, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (%wb)	% TS (%wb)	% N (%db)	% C (%+H313db)	C/N
Blank		2						
Blank		2						
Blank Mean		2.000						
Standard		9	5.00					
Standard		15	10.00					
Standard		37	25.00					
Standard		69	50.00					
Standard		94.50	70.00					
R1	0.1	13.5	8.5	0.43				
R1	0.1	14	9.5	0.48				
R1	0.1	14	9.5	0.48				
R1	0.1	15	10	0.50				
R1 Mean				0.47	93.54	0.50	48.16	96.5
R1 Std. Dev.				0.03				
R2	0.1	26.5	19	0.95				
R2	0.1	27.5	20	1.00				
R2	0.1	29.5	21	1.05				
R2	0.1	29	20.5	1.03				
R2 Mean				1.01	93.06	1.08	47.65	44.3
R2 Std. Dev.				0.04				
R3	0.1	43.5	31	1.55				
R3	0.1	42	30.5	1.53				
R3	0.1	46.5	34	1.70				
R3	0.1	45.5	33	1.65				
R3 Mean				1.61	93.13	1.72	47.82	27.9
R3 Std. Dev.				0.08				
R4	0.1	59	43	2.15				
R4	0.1	62.5	45.5	2.28				
R4	0.1	61.5	42	2.10				
R4	0.1	61	44.5	2.23				
R4 Mean				2.19	93.54	2.33	47.82	20.5
R4 Std. Dev.				0.08				

RUN #1 DATA

Bulk Density - Core Method - composted Date: March 20, 1998

Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	1	170.14	262.15	205.44	245	245	0.38	0.14	1.18	0.88	0.09	0.79
R1	10	174.86	281.05	215.65	245	265	0.40	0.17	1.22	0.86	0.10	0.76
R1 Mean							0.39	0.16	1.20	0.87	0.10	0.77
R1 Std. Dev.							0.02	0.02	0.03	0.01	0.01	0.02
R2	2	166.22	274.14	206.27	265	240	0.41	0.17	1.31	0.87	0.11	0.77
R2	B1	172.45	285.71	214.36	275	250	0.41	0.17	1.29	0.87	0.11	0.76
R2 Mean							0.41	0.17	1.30	0.87	0.11	0.77
R2 Std. Dev.							0.00	0.00	0.01	0.00	0.00	0.00
R3	F	171.64	277.97	211.31	260	260	0.41	0.15	1.31	0.88	0.10	0.78
R3	3	169.03	287.15	213.19	275	245	0.43	0.18	1.34	0.87	0.11	0.75
R3 Mean							0.42	0.17	1.32	0.87	0.10	0.77
R3 Std. Dev.							0.01	0.02	0.02	0.01	0.01	0.02
R4	K	167.22	281.60	209.63	265	245	0.43	0.17	1.36	0.87	0.11	0.76
R4	T	175.44	285.04	219.43	280	250	0.43	0.18	1.47	0.88	0.11	0.77
R4 Mean							0.43	0.17	1.42	0.88	0.11	0.77
R4 Std. Dev.							0.00	0.00	0.08	0.01	0.00	0.00

Particle Density - Pycronometer Method - composted Date: April 1, 1996

Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	T	189.73	243.92	495.41	492.16	1.16
R1	35	124.67	150.29	258.43	256.66	1.22
R1 Mean						1.20
R1 Std. Dev.						0.03
R2	C	102.61	126.80	227.94	225.81	1.31
R2	A	120.75	165.06	376.41	372.69	1.29
R2 Mean						1.30
R2 Std. Dev.						0.01
R3	35	124.85	149.85	258.00	256.8	1.31
R3	T	189.73	245.41	497.45	492.15	1.34
R3 Mean						1.32
R3 Std. Dev.						0.02
R4	A	120.76	164.36	377.17	372.85	1.36
R4	C	102.60	122.72	228.20	225.81	1.47
R4 Mean						1.42
R4 Std. Dev.						0.08

RUN #1 DATA

Volatile Solids Reduction										
Reactor	Feedstock Weight (g)	Feedstock% MC (%wb)	Feedstock %VS (%db)	Total Feedstock VS (g)	Compost Weight (g)	Compost % MC (%wb)	Compost %VS (%db)	Total Compost VS (g)	% VS Reduction (%)	$\Delta VS/\Delta t$ (%/day)
R1	726.4	60.39	86.75	249.6	696.1	61.87	84.60	224.54	10.04	0.65
R1	726.4	60.39	88.46	254.5	696.1	61.87	84.91	225.36	11.46	0.74
R1	726.4	60.39	86.60	249.2	696.1	61.87	85.83	227.80	8.58	0.56
R1	726.4	60.39	87.87	252.8	696.1	61.87	84.91	225.37	10.66	0.70
R1 Mean									10.23	0.66
R1 Std. Dev.									1.25	0.08
R2	730.3	60.88	85.89	245.4	695.5	63.03	83.33	214.27	12.68	0.80
R2	730.3	60.88	86.28	246.5	695.5	63.03	84.57	217.45	11.79	0.74
R2	730.3	60.88	86.70	247.7	695.5	63.03	83.96	215.88	12.86	0.81
R2	730.3	60.88	86.90	248.3	695.5	63.03	84.84	218.15	12.14	0.76
R2 Mean									12.37	0.78
R2 Std. Dev									0.49	0.03
R3	736.1	60.05	88.35	259.9	703.4	62.76	84.43	221.18	14.88	0.90
R3	736.1	60.05	86.04	253.1	703.4	62.76	84.27	220.76	12.76	0.77
R3	736.1	60.05	86.98	255.8	703.4	62.76	85.65	224.38	12.29	0.74
R3	736.1	60.05	87.76	258.1	703.4	62.76	85.18	223.14	13.55	0.82
R3 Mean									13.37	0.81
R3 Std. Dev.									1.13	0.07
R4	743.4	58.76	89.34	273.9	711.9	62.94	84.01	221.62	19.08	1.13
R4	743.4	58.76	86.58	265.4	711.9	62.94	83.85	221.19	16.66	0.98
R4	743.4	58.76	85.22	261.2	711.9	62.94	85.21	224.78	13.96	0.82
R4	743.4	58.76	87.91	269.5	711.9	62.94	84.26	222.27	17.52	1.04
R4 Mean									16.81	0.99
R4 Std. Dev.									2.15	0.13

Run #1

Compaction Results (12kg load)
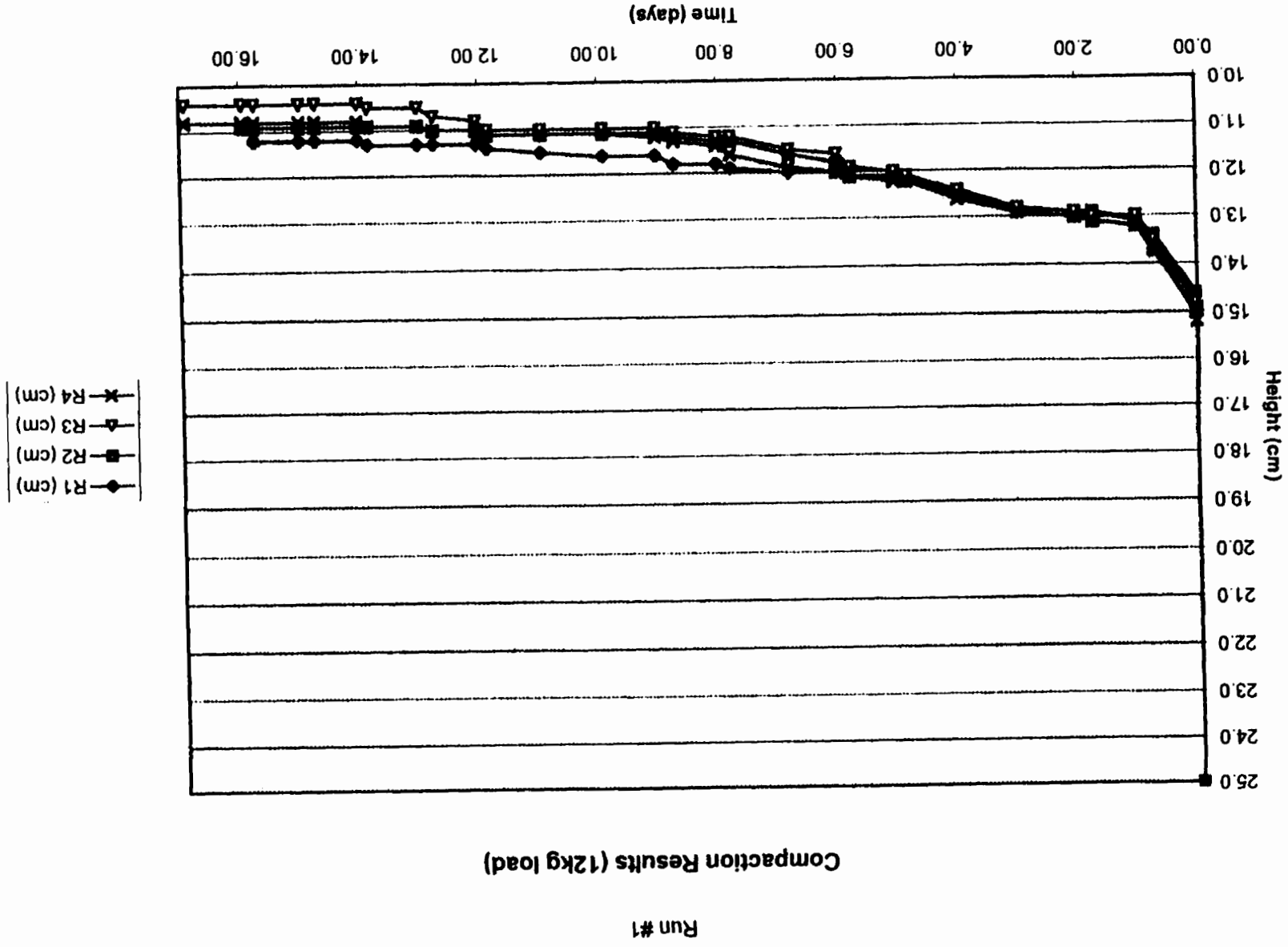
Run #1

Free Air Space Results (12 kg load)
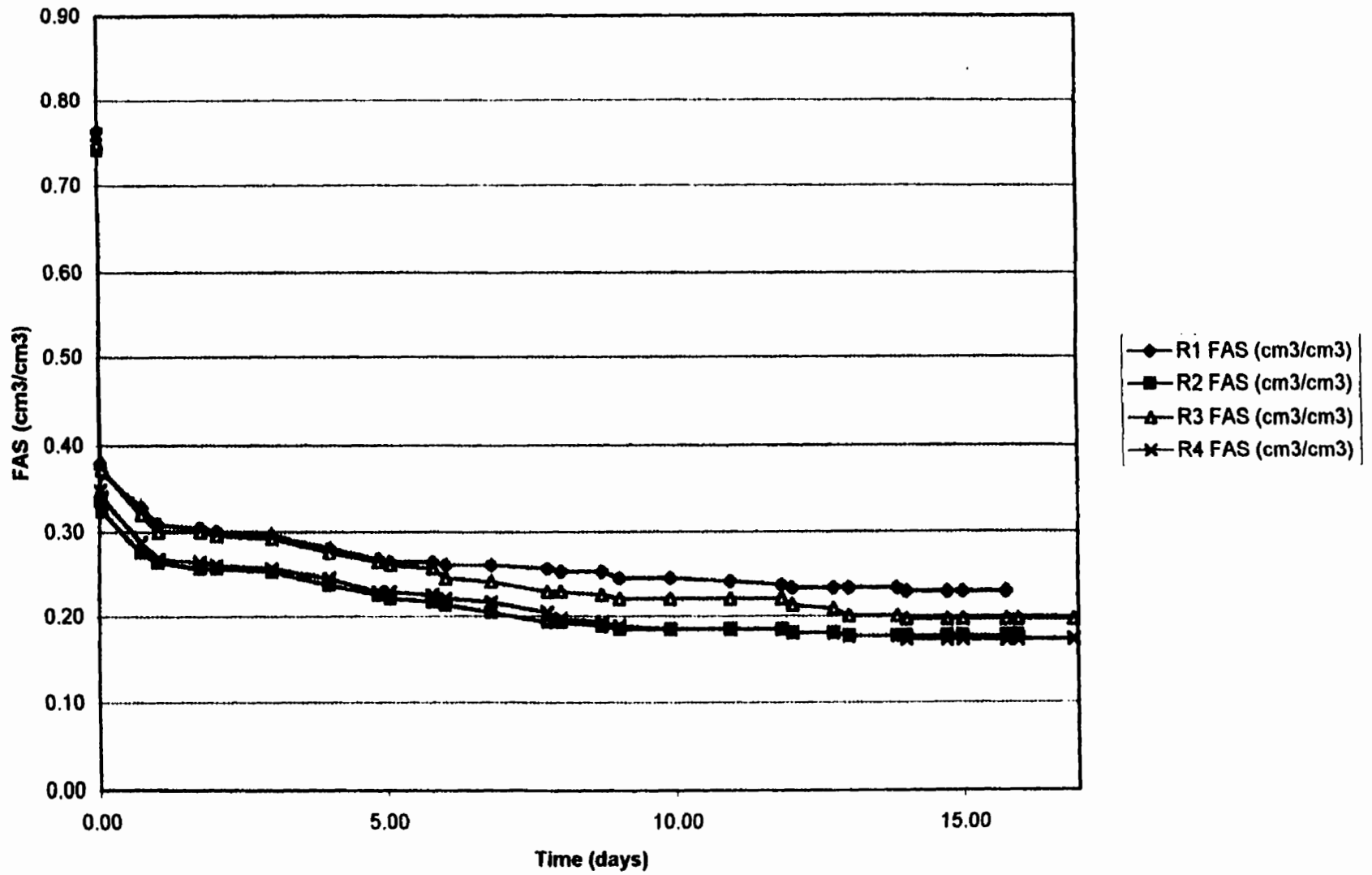
Temperature Rusults (Run #1)

Run #1

Volatile Solids Reduction - Run #1

C:N Ratio

VS Reduction (%)

Legend: 90:1, 50:1, 30:1, 20:1

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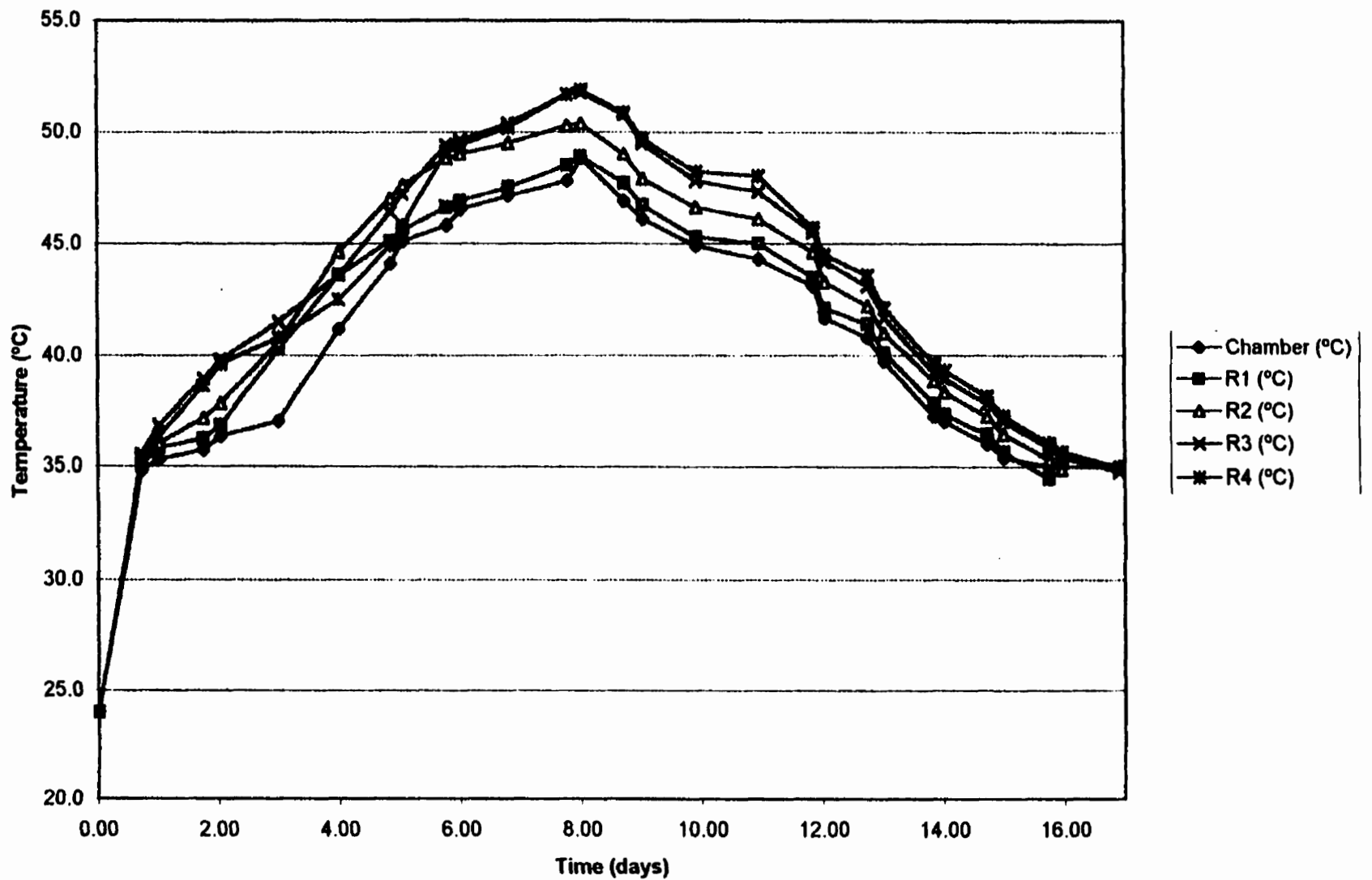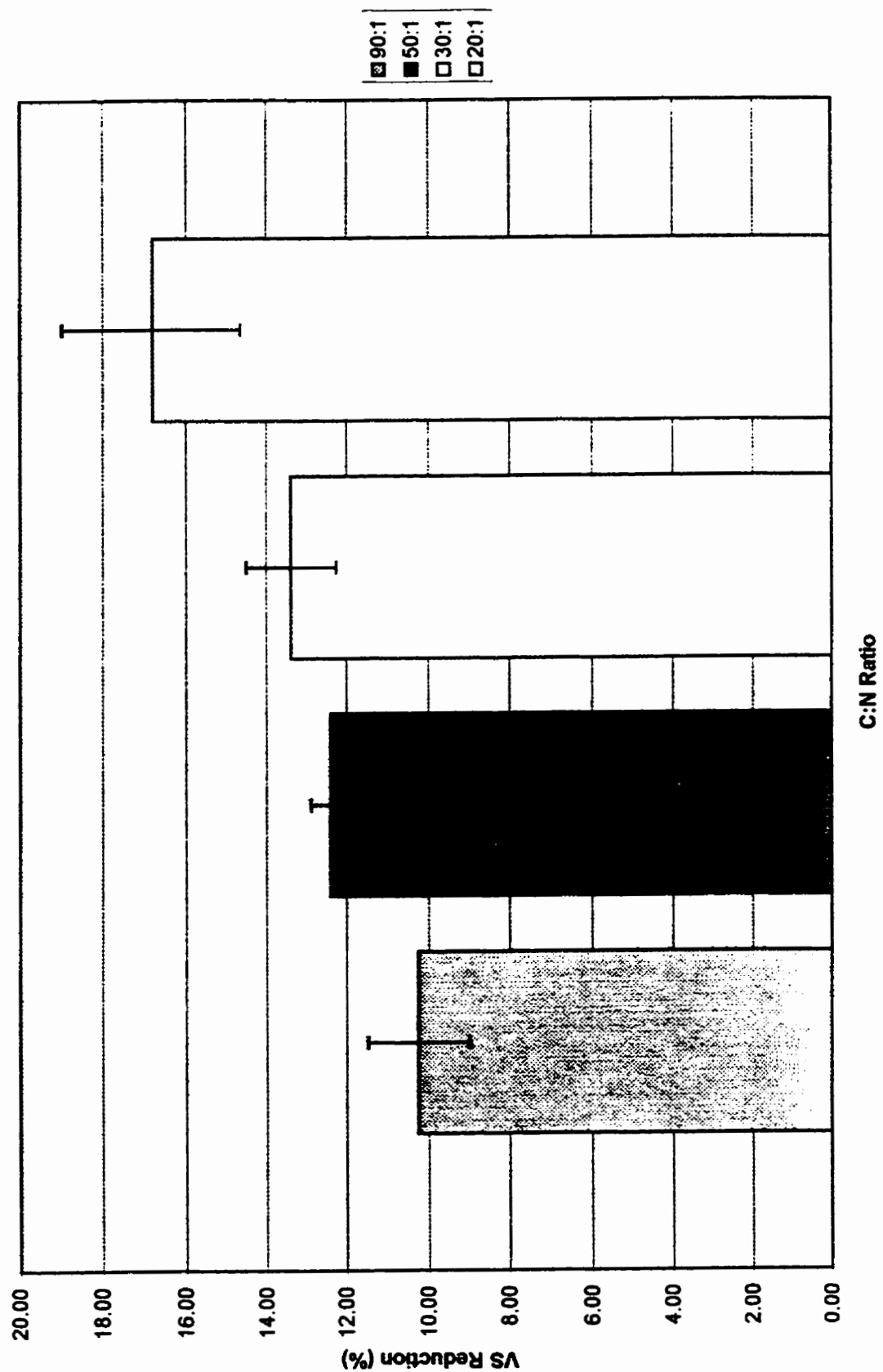
RUN #2 DATA

Kevin Larsen Thesis Composting Experiment

Run #2

74.5% Primary, 6.5% Secondary, 19% Dip

Calculations for Required Fertilizer Addition for Desired Initial C:N Ratios for 0.75 kg bark / kg biosolids
(using feedstock characterization data)

Desired C:N Ratio	%N of Fertilizer	%N of Sludge/Bark Mixture	% Carbon	% Fertilizer Required	Weight of Compost (g)	Weight of Fertilizer Required (g)
91:1	32	0.53	47.96	0	726.41	0
50:1	32	0.53	47.96	0.54	726.41	3.93
30:1	32	0.53	47.96	1.34	726.41	9.73
20:1	32	0.53	47.96	2.34	726.41	16.99

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RUN #2 DATA

Solids Data - precomposted			Date: March 23, 1998							
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	23	90.55	96.66	93.07	90.82	41.24	58.76	89.29	10.71	49.60
R1	43	83.77	89.87	86.26	84.04	40.82	59.18	89.16	10.84	49.53
R1	11	81.62	91.59	85.57	82.14	39.62	60.38	86.84	13.16	48.24
R1	118	103.92	113.48	107.63	104.48	38.81	61.19	84.91	15.09	47.17
R1 Mean						40.12	59.88	87.55	12.45	48.64
R1 Std. Dev.						1.11	1.11	2.09	2.09	1.16
R2	57	91.60	100.58	95.12	92.05	39.20	60.80	87.22	12.78	48.45
R2	111	91.30	102.91	95.76	91.93	38.42	61.58	85.87	14.13	47.71
R2	35	92.67	103.52	96.93	93.21	39.26	60.74	87.32	12.68	48.51
R2	J-12	87.12	98.25	91.48	87.66	39.17	60.83	87.61	12.39	48.67
R2 Mean						39.01	60.99	87.01	12.99	48.34
R2 Std. Dev.						0.40	0.40	0.77	0.77	0.43
R3	1	90.38	99.12	93.84	90.79	39.59	60.41	88.15	11.85	48.97
R3	47	84.10	94.00	87.95	84.55	38.89	61.11	88.31	11.69	49.06
R3	J-15	71.63	79.12	74.48	71.97	38.05	61.95	88.07	11.93	48.93
R3	51	81.00	92.56	85.49	81.55	38.84	61.16	87.75	12.25	48.75
R3 Mean						38.84	61.16	88.07	11.93	48.93
R3 Std. Dev.						0.63	0.63	0.24	0.24	0.13
R4	4	91.92	101.70	95.79	92.41	39.57	60.43	87.34	12.66	48.52
R4	2	91.88	100.17	95.01	92.34	37.76	62.24	85.30	14.70	47.39
R4	27	96.82	106.72	100.71	97.34	39.29	60.71	86.63	13.37	48.13
R4	7	85.70	93.84	89.01	86.12	40.66	59.34	87.31	12.69	48.51
R4 Mean						39.32	60.68	86.65	13.35	48.14
R4 Std. Dev.						1.20	1.20	0.95	0.95	0.53

^ OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Lieo 1995), where OC and FS are based on the dry weight fraction

RUN #2 DATA

TKN Prepared Samples Solids Data - precomposted					Date: April 2, 1998					
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^A (%db)
R1	47	84.10	89.00	88.76	84.68	95.10	4.90	87.55	12.45	48.64
R1	2	91.87	96.29	96.07	92.38	95.02	4.98	87.86	12.14	48.81
R1	23	90.54	95.61	95.35	91.13	94.87	5.13	87.73	12.27	48.74
R1	J-12	87.12	92.67	92.41	87.70	95.32	4.68	89.04	10.96	49.48
R1 Mean						95.08	4.92	88.05	11.95	48.91
R1 Std. Dev.						0.18	0.18	0.67	0.67	0.37
R2	118	103.92	109.95	109.65	104.58	95.02	4.98	88.48	11.52	49.16
R2	57	91.60	98.18	97.85	92.30	94.98	5.02	88.80	11.20	49.33
R2	1	90.40	97.26	96.89	91.13	94.61	5.39	88.75	11.25	49.31
R2	35	92.66	100.52	100.09	93.51	94.53	5.47	88.56	11.44	49.20
R2 Mean						94.79	5.21	88.65	11.35	49.25
R2 Std. Dev.						0.25	0.25	0.15	0.15	0.08
R3	J-15	71.64	76.75	76.55	72.25	96.09	3.91	87.58	12.42	48.65
R3	11	81.62	89.84	89.49	82.62	95.74	4.26	87.29	12.71	48.50
R3	7	85.71	94.27	93.90	86.75	95.68	4.32	87.30	12.70	48.50
R3	27	96.82	104.19	103.88	97.75	95.79	4.21	86.83	13.17	48.24
R3 Mean						95.82	4.18	87.25	12.75	48.47
R3 Std. Dev.						0.18	0.18	0.31	0.31	0.17
R4	111	91.30	99.22	98.77	92.23	94.32	5.68	87.55	12.45	48.64
R4	4	91.92	99.47	99.04	92.81	94.30	5.70	87.50	12.50	48.61
R4	51	80.98	88.25	87.83	81.84	94.22	5.78	87.45	12.55	48.58
R4	43	83.77	92.23	91.77	84.75	94.56	5.44	87.75	12.25	48.75
R4 Mean						94.35	5.65	87.56	12.44	48.65
R4 Std. Dev.						0.15	0.15	0.13	0.13	0.07

^A OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

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RUN #2 DATA

TKN Data - precomposted			Date: April 3, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (%wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
Blank		4						
Blank		4.5						
Blank Mean		4.3						
Standard		11.5	5.00					
Standard		17.5	10.00					
Standard		38.5	25.00					
Standard		75	50.00					
Standard		103.00	70.00					
R1	0.1	17	9.5	0.48				
R1	0.1	16.5	9.0	0.45				
R1	0.1	14	7.5	0.38				
R1	0.1	13.5	7.0	0.35				
R1 Mean				0.41	95.08	0.43	48.91	113.0
R1 Std. Dev.				0.06				
R2	0.1	21	12.0	0.60				
R2	0.1	29	18.0	0.90				
R2	0.1	29	18	0.90				
R2	0.1	28	17	0.85				
R2 Mean				0.81	94.79	0.85	49.25	57.6
R2 Std. Dev.				0.14				
R3	0.1	49.5	32.5	1.63				
R3	0.1	44	29.0	1.45				
R3	0.1	49.5	32.5	1.63				
R3	0.1	40	25.5	1.28				
R3 Mean				1.49	95.82	1.56	48.47	31.1
R3 Std. Dev.				0.17				
R4	0.1	89.5	60.5	3.03				
R4	0.1	73	49.0	2.45				
R4	0.1	90	61.0	3.05				
R4	0.1	96	66.0	3.30				
R4 Mean				2.86	94.35	3.12	48.65	15.6
R4 Std. Dev.				0.36				

RUN #2 DATA

Particle Density - Pycronometer Method - precomposted					Date: April 2, 1998
Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³					
Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	D	128.58	143.51	376.02	376.25	0.96
R1	B	107.59	148.65	372.56	371.04	1.10
R1 Mean						1.03
R1 Std. Dev.						0.10
R2	C	102.59	121.92	224.53	224.12	1.06
R2	D	128.56	132.77	374.26	374.31	0.97
R2 Mean						1.01
R2 Std. Dev.						0.06
R3	T	189.73	221.04	490.96	491.56	0.95
R3	C	102.60	135.69	226.43	226.01	1.03
R3 Mean						0.99
R3 Std. Dev.						0.06
R4	35	124.87	149.16	255.66	254.98	1.07
R4	A	120.74	129.66	374.25	374.29	0.99
R4 Mean						1.03
R4 Std. Dev.						0.06

RUN #2 DATA

Bulk Density - Core Method - precomposted				Date: April 1, 1998								
Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	10	174.90	251.11	212.13	240	230	0.32	0.16	0.96	0.83	0.10	0.73
R1	F	171.63	263.56	216.46	285	270	0.32	0.17	1.10	0.85	0.10	0.75
R1 Mean							0.32	0.16	1.03	0.84	0.10	0.74
R1 Std. Dev.							0.00	0.00	0.10	0.01	0.00	0.01
R2	T	163.36	245.60	196.83	240	215	0.34	0.16	1.06	0.85	0.10	0.76
R2	K	171.78	252.36	213.05	255	240	0.32	0.17	0.97	0.82	0.11	0.72
R2 Mean							0.33	0.16	1.01	0.84	0.10	0.74
R2 Std. Dev.							0.02	0.01	0.06	0.02	0.01	0.03
R3	1	178.21	254.90	208.68	245	225	0.31	0.14	0.95	0.86	0.08	0.77
R3	A	176.98	241.63	210.11	205	195	0.32	0.17	1.03	0.84	0.10	0.73
R3 Mean							0.31	0.15	0.99	0.85	0.09	0.75
R3 Std. Dev.							0.00	0.02	0.06	0.02	0.01	0.03
R4	B1	172.48	250.43	205.11	240	220	0.32	0.15	1.07	0.86	0.09	0.77
R4	D	168.22	251.98	215.37	260	245	0.32	0.19	0.99	0.80	0.12	0.69
R4 Mean							0.32	0.17	1.03	0.83	0.10	0.73
R4 Std. Dev.							0.00	0.03	0.06	0.04	0.02	0.06

RUN #2 DATA

Run #3 started March 19, 1998 @ 2:00 pm
Reactors aerated at a flow rate of approximately 15mL/sec for 5 min every hour
At time zero, the thermostat on the chamber was set to an initial temp. of 35°C.

Compaction Data

Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	R1 (cm)	R2 (cm)	R3 (cm)	R4 (cm)
March	19	14:00	0.0	0.00	25.0	25.0	25.0	25.0
	19	14:30	0.5	0.02	15.3	15.2	15.1	15.1
	19	15:30	1.5	0.06	15.2	15.1	14.9	15.0
	20	9:00	19.0	0.79	14.0	13.3	13.4	14.0
	20	16:00	26.0	1.08	13.5	13.1	13.1	13.4
	21	14:30	48.5	2.02	13.2	12.9	13.0	13.1
	22	13:30	71.5	2.98	13.0	12.8	12.8	13.0
	23	11:30	93.5	3.90	12.7	12.3	12.4	12.4
	23	16:00	98.0	4.08	12.5	12.2	12.3	12.4
	24	10:30	116.5	4.85	12.2	12.0	12.1	12.3
	24	15:30	121.5	5.06	12.2	12.0	12.1	12.2
	25	10:30	140.5	5.85	12.1	11.8	11.9	12.1
	25	16:00	146.0	6.08	12.1	11.8	11.8	12.0
	26	8:30	162.5	6.77	12.0	11.6	11.5	11.9
	26	16:00	170.0	7.08	12.0	11.5	11.4	11.8
	27	9:00	187.0	7.79	11.9	11.2	11.2	11.6
	27	16:00	194.0	8.08	11.9	11.2	11.1	11.4
	28	14:00	216.0	9.00	11.9	11.1	11.0	11.2
	29	12:00	238.0	9.92	11.8	11.0	11.0	11.1
	30	8:30	258.5	10.77	11.8	11.0	11.0	11.0
	30	15:00	265.0	11.04	11.7	11.0	11.0	11.0
	31	11:00	285.0	11.88	11.7	11.0	10.9	11.0
	31	16:00	290.0	12.08	11.8	11.0	10.9	11.0
April	1	11:30	309.5	12.90	11.6	10.9	10.9	11.0
	1	16:00	314.0	13.08	11.6	10.9	10.7	11.0
	2	11:00	333.0	13.88	11.5	10.8	10.7	11.0
	2	16:30	338.5	14.10	11.5	10.7	10.7	11.0
	3	11:00	357.0	14.88	11.5	10.7	10.6	11.0
	4	11:30	381.5	15.90	11.4	10.7	10.6	11.0
	5	13:00	407.0	16.96	11.4	10.7	10.5	10.9
	6	9:30	427.5	17.81			10.5	10.9
	6	15:30	433.0	18.04			10.5	10.9

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RUN #2 DATA

Temperature Data									
Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	Chamber (°C)	R1 (°C)	R2 (°C)	R3 (°C)	R4 (°C)
March	19	14:00	0.0	0.00	24.0	24.0	24.0	24.0	24.0
	20	9:00	19.0	0.79	35.0	35.0	35.6	35.5	35.4
	20	16:00	26.0	1.08	35.4	36.0	36.6	37.2	37.0
	21	14:30	48.5	2.02	36.3	38.1	38.8	40.1	40.4
	22	13:30	71.5	2.98	38.2	41.8	41.9	42.3	41.6
	23	11:30	93.5	3.90	41.7	45.4	46.2	45.4	44.5
	23	16:00	98.0	4.08	44.7	46.0	47.1	46.1	45.1
	24	10:30	116.5	4.85	46.9	47.9	49.7	50.1	48.2
	24	15:30	121.5	5.06	47.8	48.0	49.9	50.3	48.5
	25	10:30	140.5	5.85	48.2	48.5	50.6	51.6	50.3
	25	16:00	146.0	6.08	48.4	48.6	50.7	51.8	50.5
	26	8:30	162.5	6.77	48.7	48.9	50.9	52.2	51.8
	26	16:00	170.0	7.08	48.9	49.0	51.1	52.7	52.3
	27	9:00	187.0	7.79	48.9	49.1	51.2	52.8	53.3
	27	16:00	194.0	8.08	48.6	49.0	51.0	52.6	53.0
	28	14:00	216.0	9.00	47.5	47.9	49.6	51.1	51.8
	29	12:00	238.0	9.92	46.5	46.8	48.2	49.4	50.1
	30	8:30	258.5	10.77	44.9	45.3	46.7	47.8	48.2
	30	15:00	265.0	11.04	43.4	44.2	45.6	46.6	47.1
	31	11:00	285.0	11.88	42.5	42.9	44.2	45.1	45.7
	31	16:00	290.0	12.08	42.2	42.5	43.5	44.6	45.0
April	1	11:30	309.5	12.90	41.0	41.4	42.6	43.5	43.7
	1	16:00	314.0	13.08	40.7	40.9	41.8	42.7	43.0
	2	11:00	333.0	13.88	39.3	39.7	40.5	41.3	41.5
	2	16:30	338.5	14.10	38.4	39.0	39.9	40.6	40.7
	3	11:00	357.0	14.88	38.3	38.5	39.0	39.7	39.9
	4	11:30	381.5	15.90	36.4	36.5	36.9	37.4	37.6
	5	13:00	407.0	16.96	35.0	34.8	35.0	35.5	36.0
	6	9:30	427.5	17.81	35.0			34.9	35.6
	6	15:30	433.0	18.04	35.0				35.0

RUN #2 DATA

Physical Analysis for Loading Effect on FAS of Composting Mixture - 12 kg load				
Time (days)	R1 FAS (cm³/cm³)	R2 FAS (cm³/cm³)	R3 FAS (cm³/cm³)	R4 FAS (cm³/cm³)
0.00	0.74	0.74	0.75	0.73
0.02	0.39	0.35	0.38	0.34
0.06	0.39	0.34	0.38	0.34
0.79	0.34	0.27	0.32	0.30
1.08	0.32	0.26	0.30	0.28
2.02	0.31	0.26	0.30	0.26
2.98	0.30	0.25	0.29	0.26
3.90	0.29	0.23	0.28	0.24
4.08	0.28	0.23	0.27	0.24
4.85	0.27	0.22	0.26	0.23
5.06	0.27	0.22	0.26	0.23
5.85	0.26	0.21	0.26	0.22
6.08	0.26	0.21	0.25	0.22
6.77	0.26	0.20	0.24	0.22
7.08	0.26	0.20	0.24	0.21
7.79	0.26	0.19	0.23	0.20
8.08	0.26	0.19	0.22	0.20
9.00	0.26	0.18	0.22	0.19
9.92	0.25	0.18	0.22	0.18
10.77	0.25	0.18	0.22	0.18
11.04	0.25	0.18	0.22	0.18
11.88	0.25	0.18	0.22	0.18
12.08	0.24	0.18	0.22	0.18
12.90	0.24	0.18	0.21	0.18
13.06	0.24	0.18	0.21	0.18
13.88	0.24	0.17	0.21	0.18
14.10	0.24	0.17	0.20	0.18
14.88	0.24	0.17	0.20	0.18
15.90	0.24	0.17	0.20	0.18
16.96		0.17	0.20	0.18
17.81			0.20	0.18

RUN #2 DATA

Solids Data - composted			Date: April 3, 1998							
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^A (%db)
R1	111	91.30	112.54	99.67	92.47	39.41	60.59	86.02	13.98	47.79
R1	45	83.19	105.70	91.91	84.47	38.74	61.26	85.32	14.68	47.40
R1	47	84.09	105.70	92.5	85.28	38.92	61.08	85.85	14.15	47.69
R1	7	85.71	106.16	93.86	86.81	39.85	60.15	86.50	13.50	48.06
R1 Mean						39.23	60.77	85.92	14.08	47.74
R1 Std. Dev.						0.50	0.50	0.49	0.49	0.27
R2	J-12	87.12	107.38	94.70	88.29	37.41	62.59	84.56	15.44	46.98
R2	3	90.93	109.99	98.08	91.98	37.51	62.49	85.31	14.69	47.40
R2	51	81.00	101.19	88.57	82.11	37.49	62.51	85.34	14.66	47.41
R2	35	92.65	111.76	99.74	93.77	37.10	62.90	84.20	15.80	46.78
R2 Mean						37.38	62.62	84.85	15.15	47.14
R2 Std. Dev.						0.19	0.19	0.56	0.56	0.31
R3	27	96.83	119.89	105.46	98.18	37.42	62.58	84.36	15.64	46.86
R3	57	91.61	113.42	99.79	92.96	37.51	62.49	83.50	16.50	46.39
R3	43	83.76	103.60	91.28	84.98	37.90	62.10	83.78	16.22	46.54
R3	2	91.86	115.88	100.99	93.26	38.01	61.99	84.67	15.33	47.04
R3 Mean						37.71	62.28	84.07	15.93	46.71
R3 Std. Dev.						0.29	0.29	0.53	0.53	0.30
R4	118	103.92	129.65	113.59	106.11	37.58	62.42	77.35	22.65	42.97
R4	23	90.56	110.10	97.92	91.93	37.67	62.33	81.39	18.61	45.21
R4	J-15	71.64	88.83	78.16	72.76	37.93	62.07	82.82	17.18	46.01
R4	30	94.17	117.21	102.83	95.96	37.59	62.41	79.33	20.67	44.07
R4 Mean						37.69	62.31	80.22	19.78	44.57
R4 Std. Dev.						0.16	0.16	2.39	2.39	1.33

^A OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

TKN Prepared Samples Solids Data - composted						Date: April 15, 1998				
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	111	91.30	100.21	99.47	92.37	91.69	8.31	86.90	13.10	48.28
R1	7	85.70	94.73	93.97	86.77	91.58	8.42	87.06	12.94	48.37
R1	3	90.93	98.18	97.59	91.81	91.86	8.14	86.79	13.21	48.21
R1	23	90.54	98.14	97.51	91.45	91.71	8.29	86.94	13.06	48.30
R1 Mean						91.71	8.28	86.92	13.08	48.29
R1 Std. Dev.						0.11	0.11	0.11	0.11	0.06
R2	51	80.97	88.15	87.57	81.86	91.92	8.08	86.52	13.48	48.06
R2	118	103.92	110.31	109.79	104.69	91.86	8.14	86.88	13.12	48.27
R2	J-12	87.12	94.47	93.88	88.04	91.97	8.03	86.39	13.61	47.99
R2	J-15	71.63	77.38	76.91	72.34	91.83	8.17	86.55	13.45	48.09
R2 Mean						91.90	8.10	86.59	13.41	48.10
R2 Std. Dev.						0.06	0.06	0.21	0.21	0.12
R3	27	96.83	105.00	104.27	97.92	91.06	8.94	85.35	14.65	47.42
R3	43	83.76	90.91	90.32	84.70	91.75	8.25	85.67	14.33	47.59
R3	35	92.66	99.72	99.12	93.55	91.50	8.50	86.22	13.78	47.90
R3	57	91.60	99.58	98.87	92.63	91.10	8.90	85.83	14.17	47.68
R3 Mean						91.35	8.65	85.77	14.23	47.65
R3 Std. Dev.						0.33	0.33	0.36	0.36	0.20
R4	47	84.10	93.04	92.27	85.22	91.39	8.61	86.29	13.71	47.94
R4	45	83.21	92.01	91.27	84.28	91.59	8.41	86.72	13.28	48.18
R4	30	94.16	102.92	102.16	95.24	91.32	8.68	86.50	13.50	48.06
R4	25	92.17	101.81	100.99	93.38	91.49	8.51	86.28	13.72	47.93
R4 Mean						91.45	8.55	86.45	13.55	48.03
R4 Std. Dev.						0.12	0.12	0.21	0.21	0.12

^ OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Lieo 1993), where OC and FS are based on the dry weight fraction

RUN #2 DATA

TKN Data - composted			Date: April 17, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (%wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
Blank		3.5						
Blank		3.5						
Blank Mean		3.500						
Standard		10.5	5.00					
Standard		18.0	10.00					
Standard		39.5	25.00					
Standard		73.5	50.00					
Standard		101.0	70.00					
R1	0.1	15	8	0.40				
R1	0.1	15	8	0.40				
R1	0.1	16	9	0.45				
R1	0.1	14	7.5	0.38				
R1 Mean				0.41	91.71	0.44	48.29	109.8
R1 Std. Dev.				0.03				
R2	0.1	30.5	19	0.95				
R2	0.1	30	19	0.95				
R2	0.1	29	18	0.90				
R2	0.1	27	17	0.85				
R2 Mean				0.91	91.90	0.98	48.10	48.8
R2 Std. Dev.				0.05				
R3	0.1	50	33	1.65				
R3	0.1	40	26	1.30				
R3	0.1	44	29	1.45				
R3	0.1	38	24.5	1.23				
R3 Mean				1.41	91.35	1.53	47.65	31.2
R3 Std. Dev.				0.19				
R4	0.1	58.5	39.5	1.98				
R4	0.1	66.5	45	2.25				
R4	0.1	67.5	46	2.30				
R4	0.1	69.5	47.5	2.38				
R4 Mean				2.23	91.45	2.42	48.03	19.9
R4 Std. Dev.				0.17				

RUN #2 DATA

Particle Density - Pycronometer Method - composted
Date: April 8, 1998

Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	C	102.61	124.4	227.04	225.88	1.15
R1	A	120.74	175.39	375.63	372.86	1.15
R1 Mean						1.15
R1 Std. Dev.						0.01
R2	35	124.86	151.00	258.50	256.66	1.23
R2	T	189.72	245.82	497.26	492.11	1.32
R2 Mean						1.28
R2 Std. Dev.						0.07
R3	A	120.75	170.37	377.15	372.82	1.30
R3	35	124.86	154.58	259.61	256.81	1.33
R3 Mean						1.31
R3 Std. Dev.						0.02
R4	T	189.72	247.35	497.86	492.18	1.35
R4	C	102.62	131.59	228.76	225.81	1.37
R4 Mean						1.36
R4 Std. Dev.						0.01

Bulk Density - Core Method - composted
Date: April 7, 1998

Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	B2	173.43	269.25	210.44	240	220	0.40	0.17	1.15	0.85	0.10	0.75
R1	K	165.14	265.94	204.53	245	225	0.41	0.18	1.15	0.85	0.11	0.74
R1 Mean							0.41	0.17	1.15	0.85	0.10	0.75
R1 Std. Dev.							0.01	0.00	0.01	0.00	0.00	0.01
R2	1	170.19	284.04	204.84	225	225	0.42	0.15	1.23	0.87	0.10	0.78
R2	T	163.35	284.37	200.46	230	205	0.44	0.18	1.32	0.86	0.11	0.75
R2 Mean							0.43	0.17	1.28	0.87	0.11	0.76
R2 Std. Dev.							0.02	0.02	0.07	0.01	0.01	0.02
R3	R5	171.81	281.80	212.39	250	225	0.44	0.18	1.30	0.86	0.11	0.75
R3	A1	177.65	287.73	218.25	245	225	0.45	0.18	1.33	0.86	0.11	0.75
R3 Mean							0.44	0.18	1.31	0.86	0.11	0.76
R3 Std. Dev.							0.01	0.00	0.02	0.00	0.00	0.00
R4	G	174.91	290.48	217.56	250	225	0.46	0.19	1.35	0.86	0.12	0.74
R4	2	167.26	287.37	204.36	225	225	0.44	0.16	1.37	0.88	0.10	0.78
R4 Mean							0.45	0.18	1.36	0.87	0.11	0.76
R4 Std. Dev.							0.01	0.02	0.01	0.01	0.01	0.02

RUN #2 DATA

Reactor	Feedstock Weight (g)	Feedstock% MC (%wb)	Feedstock %VS (%db)	Total Feedstock VS (g)	Compost Weight (g)	Compost % MC (%wb)	Compost %VS (%db)	Total Compost VS (g)	% VS Reduction (%)	$\Lambda VS/\Lambda t$ (%/day)
Volatile Solids Reduction										
R1	728.4	59.88	89.29	260.2	679.5	60.77	86.02	229.30	11.88	0.71
R1	728.4	59.88	89.16	259.8	679.5	60.77	85.32	227.43	12.47	0.74
R1	728.4	59.88	86.84	253.1	679.5	60.77	85.85	228.84	9.58	0.57
R1	728.4	59.88	84.91	247.5	679.5	60.77	86.50	230.58	6.82	0.41
R1 Mean									10.19	0.61
R1 Std. Dev.									2.57	0.15
R2	730.3	60.99	87.22	248.5	685.8	62.62	84.56	216.79	12.76	0.75
R2	730.3	60.99	85.87	244.7	685.8	62.62	85.31	218.71	10.61	0.63
R2	730.3	60.99	87.32	248.8	685.8	62.62	85.34	218.77	12.07	0.71
R2	730.3	60.99	87.61	249.6	685.8	62.62	84.20	215.86	13.53	0.80
R2 Mean									12.24	0.72
R2 Std. Dev									1.24	0.07
R3	736.1	61.16	88.15	252.0	686.2	62.29	84.36	218.29	13.39	0.76
R3	736.1	61.16	88.31	252.5	686.2	62.29	83.50	216.06	14.43	0.82
R3	736.1	61.16	88.07	251.8	686.2	62.29	83.78	216.79	13.91	0.79
R3	736.1	61.16	87.75	250.9	686.2	62.29	84.67	219.09	12.68	0.72
R3 Mean									13.60	0.77
R3 Std. Dev.									0.75	0.04
R4	743.4	60.68	87.34	255.3	697.4	62.31	77.35	203.33	20.36	1.13
R4	743.4	60.68	85.30	249.3	697.4	62.31	81.39	213.93	14.20	0.79
R4	743.4	60.68	86.63	253.2	697.4	62.31	82.82	217.70	14.03	0.78
R4	743.4	60.68	87.31	255.2	697.4	62.31	79.33	208.53	18.29	1.01
R4 Mean									16.72	0.93
R4 Std. Dev.									3.12	0.17

Run #2

Compaction Results (12kg load)

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Legend:
- R1 (cm)
- R2 (cm)
- R3 (cm)
- R4 (cm)

Time (days): 0.00, 2.00, 4.00, 6.00, 8.00, 10.00, 12.00, 14.00, 16.00, 18.00

Height (cm): 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 24.0, 25.0
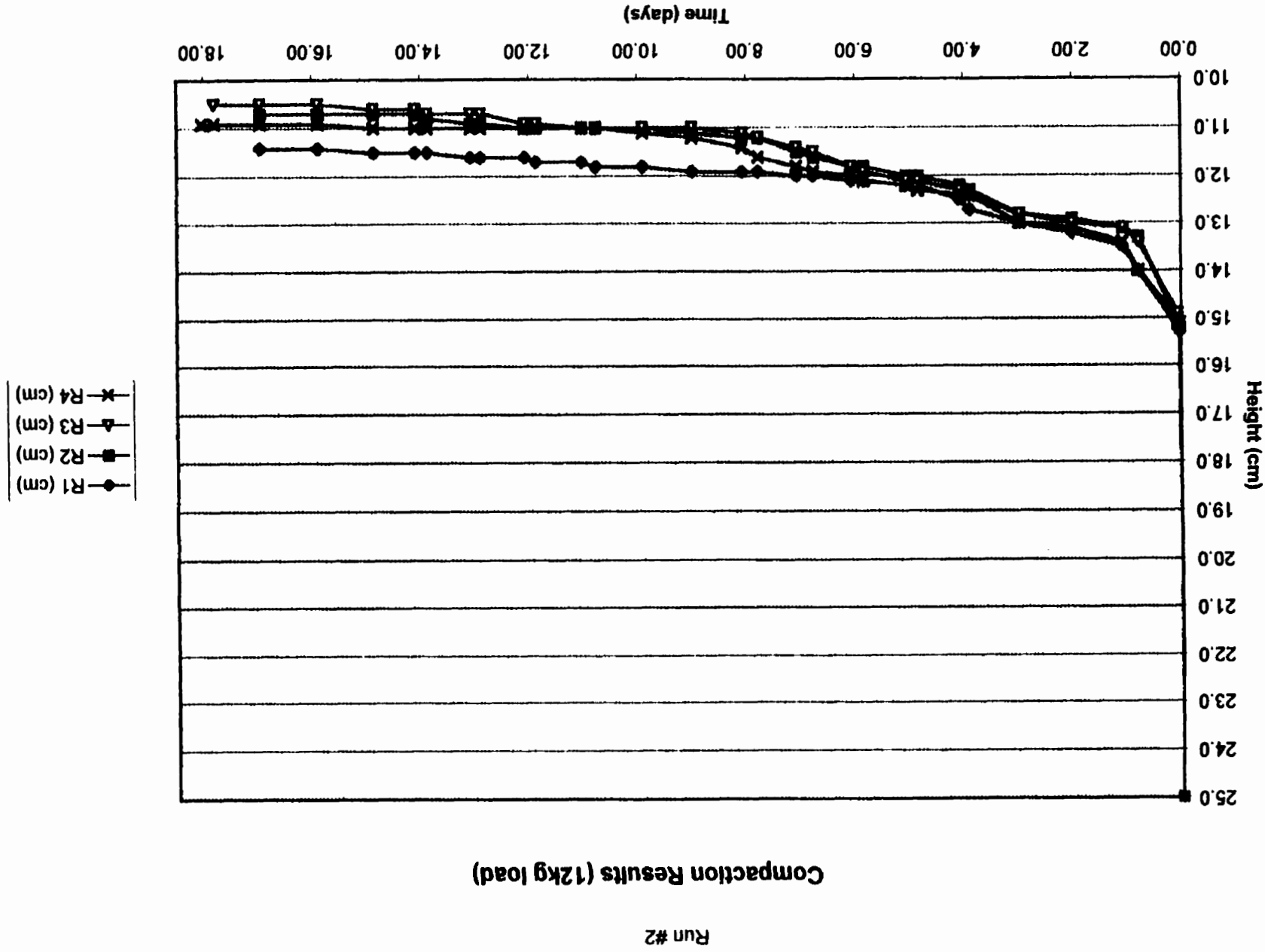
Run #2

Free Air Space Results (12 kg load)

Run #2

Temperature Rusults (Run #2)

Legend:
- Chamber (°C)
- R1 (°C)
- R2 (°C)
- R3 (°C)
- R4 (°C)

Time (days)

Temperature (°C)

Run #2

Volatile Solids Reduction - Run #2

VS Reduction (%)

C:N Ratio

Legend: 90:1, 50:1, 30:1, 20:1
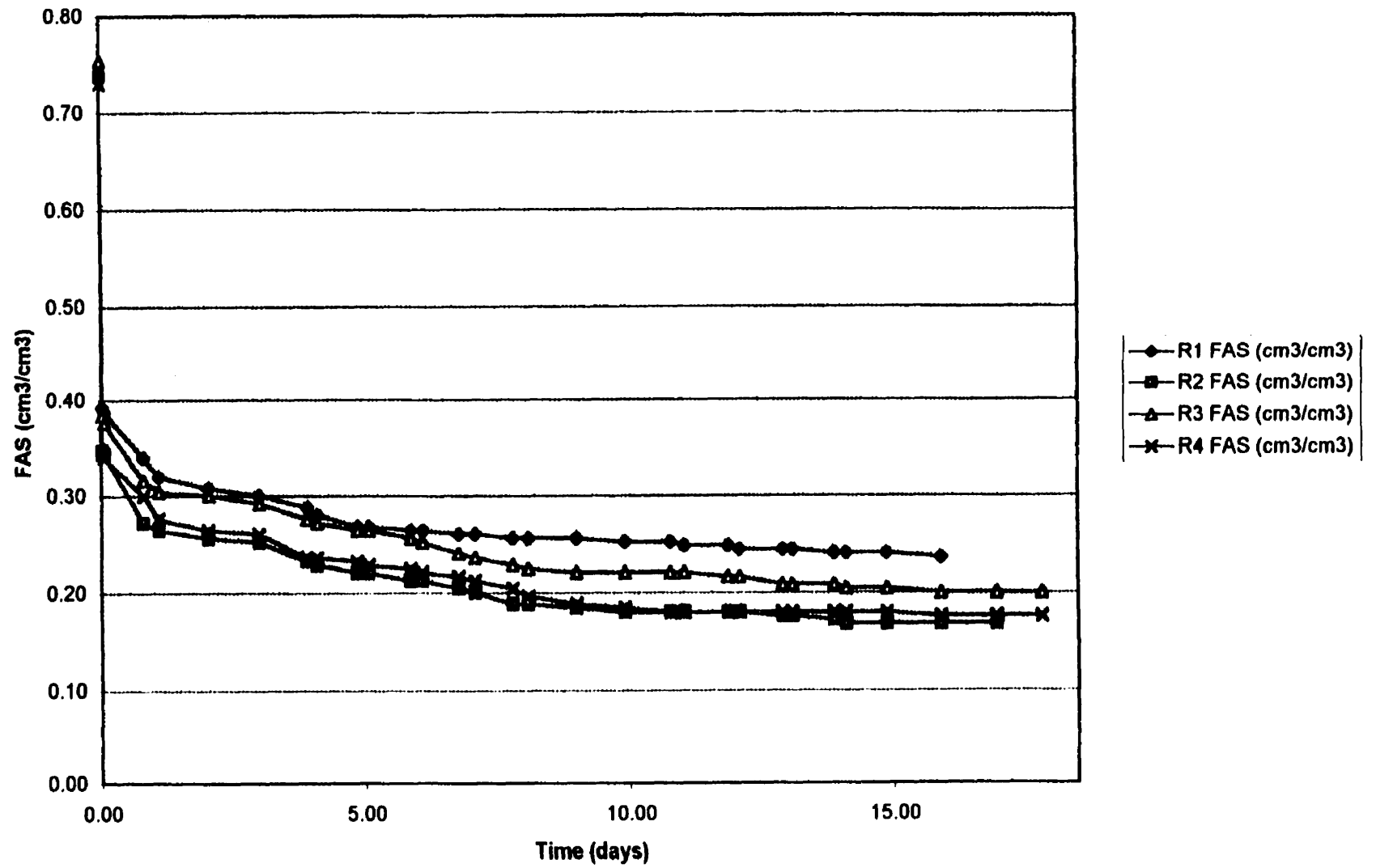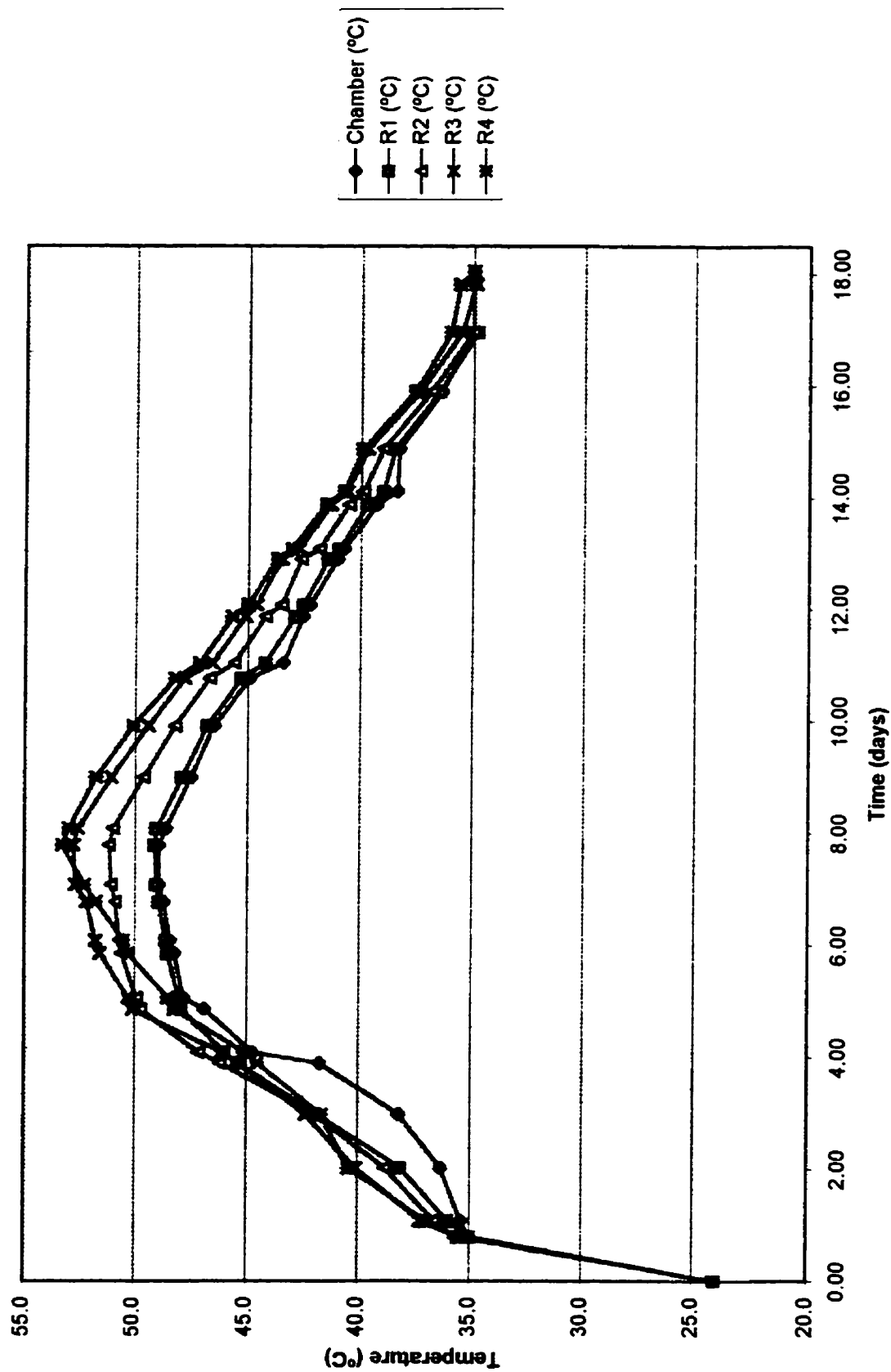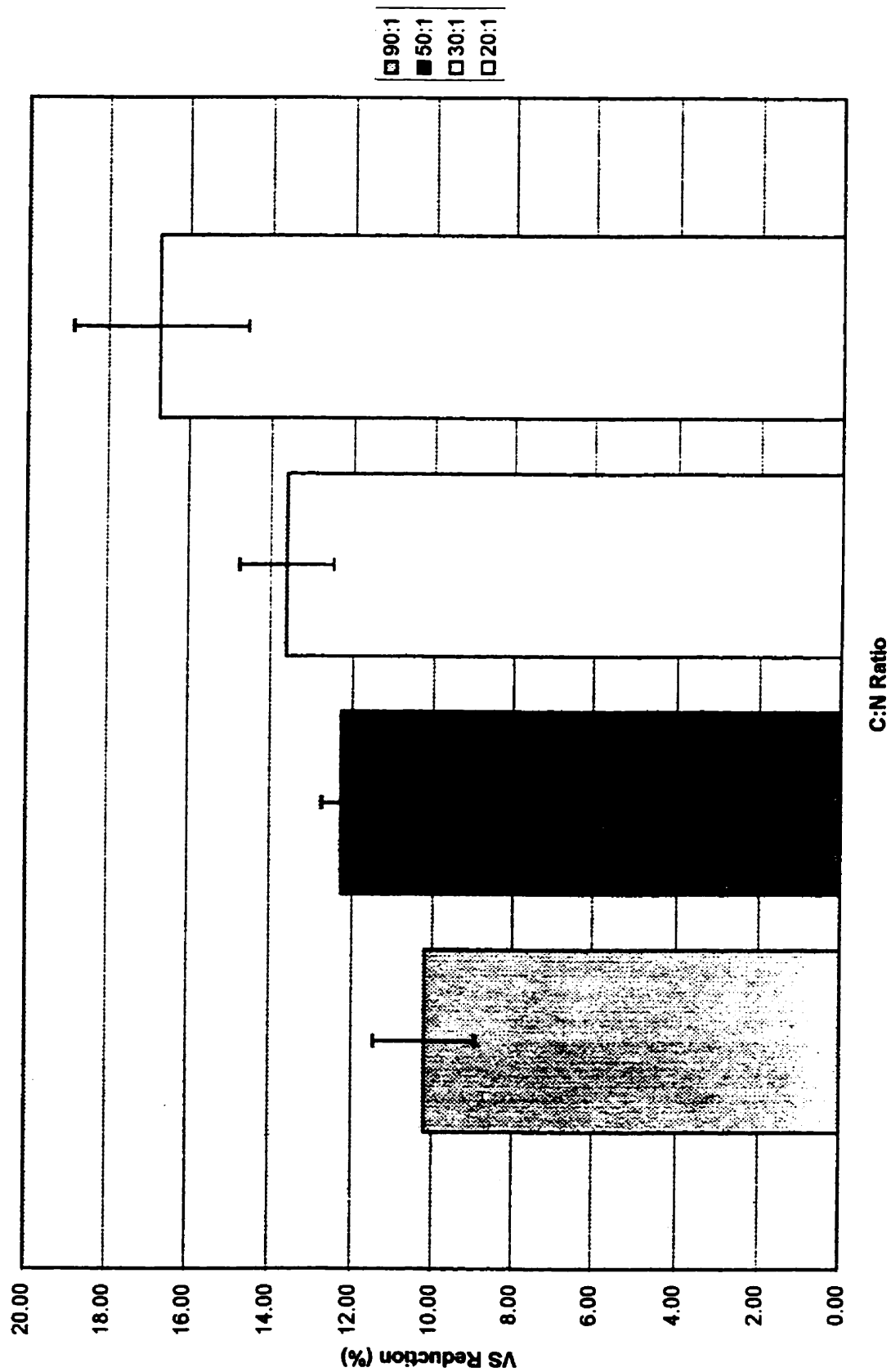
RUN #3 DATA

Kevin Larsen Thesis Composting Experiment
Run #3
74.5% Primary, 6.5% Secondary, 19% Dip

Calculations for Required Fertilizer Addition for Desired Initial C:N Ratios for 0.75 kg bark / kg biosolids (using feedstock characterization data)

Desired C:N Ratio	%N of Fertilizer	%N of Sludge/ Bark Mixture	% Carbon	% Fertilizer Required	Weight of Compost (g)	Weight of Fertilizer Required (g)
91:1	32	0.53	47.96	0	726.41	0
50:1	32	0.53	47.96	0.54	726.41	3.93
30:1	32	0.53	47.96	1.34	726.41	9.73
20:1	32	0.53	47.96	2.34	726.41	16.99

RUN #3 DATA

Solids Data - precomposted				Date: April 9, 1998						
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^X (%db)
R1	57	91.61	109.86	98.55	92.51	38.03	61.97	87.03	12.97	48.35
R1	27	96.81	113.03	103.00	97.72	38.16	61.84	85.30	14.70	47.39
R1	43	83.77	103.89	91.47	84.72	38.27	61.73	87.66	12.34	48.70
R1	25	92.18	111.12	99.62	93.11	39.28	60.72	87.50	12.50	48.61
R1 Mean						38.44	61.56	86.87	13.13	48.28
R1 Std. Dev.						0.57	0.57	1.08	1.08	0.60
R2	3	90.94	106.89	97.09	91.77	38.56	61.44	86.50	13.50	48.06
R2	111	91.30	109.02	98.61	92.10	41.25	58.75	89.06	10.94	49.48
R2	23	90.55	110.59	98.34	91.56	38.87	61.13	87.03	12.97	48.35
R2	51	80.98	103.29	89.50	82.18	38.19	61.81	85.92	14.08	47.73
R2 Mean						39.22	60.78	87.13	12.87	48.40
R2 Std. Dev.						1.38	1.38	1.36	1.36	0.76
R3	45	83.19	99.59	89.56	84.03	38.84	61.16	86.81	13.19	48.23
R3	J-12	87.12	110.32	96.48	88.13	40.34	59.66	89.21	10.79	49.56
R3	118	103.94	129.51	113.96	105.17	39.19	60.81	87.72	12.28	48.74
R3	47	84.10	102.57	91.10	85.02	37.90	62.10	86.86	13.14	48.25
R3 Mean						39.07	60.93	87.65	12.35	48.70
R3 Std. Dev.						1.01	1.01	1.12	1.12	0.62
R4	J-15	71.84	83.74	76.55	72.30	40.58	59.42	86.56	13.44	48.09
R4	30	94.16	117.43	103.32	95.40	39.36	60.64	86.46	13.54	48.03
R4	35	92.65	112.91	100.57	93.70	39.09	60.91	86.74	13.26	48.19
R4	7	85.71	105.41	93.32	86.66	38.63	61.37	87.52	12.48	48.62
R4 Mean						39.42	60.58	86.82	13.18	48.23
R4 Std. Dev.						0.83	0.83	0.48	0.48	0.27

^{X} OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #3 DATA

TKN Prepared Samples Solids Data - precomposted					Date: April 20, 1998					
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^ (%db)
R1	118	103.92	111.76	111.30	104.87	94.13	5.87	87.13	12.87	48.40
R1	J-12	87.12	96.07	95.55	88.19	94.19	5.81	87.31	12.69	48.50
R1	35	92.67	100.44	99.96	93.63	93.82	6.18	86.83	13.17	48.24
R1	57	91.62	100.52	99.98	92.67	93.93	6.07	87.44	12.56	48.58
R1 Mean						94.02	5.98	87.18	12.82	48.43
R1 Std. Dev.						0.17	0.17	0.26	0.26	0.15
R2	J-15	71.63	78.97	78.55	72.53	94.28	5.72	86.99	13.01	48.33
R2	27	96.82	104.52	104.08	97.78	94.29	5.71	86.78	13.22	48.21
R2	7	85.71	94.33	93.84	86.77	94.32	5.68	86.96	13.04	48.31
R2	111	91.30	100.88	100.34	92.45	94.36	5.64	87.28	12.72	48.49
R2 Mean						94.31	5.69	87.00	13.00	48.33
R2 Std. Dev.						0.04	0.04	0.21	0.21	0.12
R3	51	80.98	89.46	88.99	81.95	94.46	5.54	87.89	12.11	48.83
R3	3	90.95	101.65	101.08	92.17	94.67	5.33	87.96	12.04	48.86
R3	23	90.55	100.51	99.99	91.74	94.78	5.22	87.39	12.61	48.55
R3	30	94.16	103.38	102.88	95.23	94.58	5.42	87.73	12.27	48.74
R3 Mean						94.62	5.38	87.74	12.26	48.75
R3 Std. Dev.						0.14	0.14	0.25	0.25	0.14
R4	43	83.78	93.98	93.41	85.00	94.41	5.59	87.33	12.67	48.52
R4	25	92.17	99.85	99.44	93.11	94.66	5.34	87.07	12.93	48.37
R4	47	84.09	91.81	91.39	85.05	94.56	5.44	86.85	13.15	48.25
R4	45	83.19	91.38	90.91	84.20	94.26	5.74	86.92	13.08	48.29
R4 Mean						94.47	5.53	87.04	12.96	48.36
R4 Std. Dev.						0.17	0.17	0.21	0.21	0.12

^ OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #3 DATA

TKN Data - precomposted			Date: April 22, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (% wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
Blank		5						
Blank		5						
Blank Mean		5.0						
Standard		13	5.00					
Standard		21	10.00					
Standard		44.5	25.00					
Standard		81.5	50.00					
R1	0.1	18.5	9.0	0.45				
R1	0.1	18	8.5	0.43				
R1	0.1	19	9.0	0.45				
R1	0.1	18.5	9.0	0.45				
R1 Mean				0.44	94.02	0.47	48.43	103.0
R1 Std. Dev.				0.01				
R2	0.1	31	17.0	0.85				
R2	0.1	32	17.5	0.88				
R2	0.1	31.5	17.5	0.88				
R2	0.1	32	17.5	0.88				
R2 Mean				0.87	94.31	0.92	48.33	52.6
R2 Std. Dev.				0.01				
R3	0.1	54	32.0	1.60				
R3	0.1	51	30.0	1.50				
R3	0.1	58	34.5	1.73				
R3	0.1	57	34.0	1.70				
R3 Mean				1.63	94.62	1.72	48.75	28.4
R3 Std. Dev.				0.10				
R4	0.1	82.5	51.0	2.55				
R4	0.1	85.5	52.5	2.63				
R4	0.1	83.5	51.0	2.55				
R4	0.1	77	47.0	2.35				
R4 Mean				2.52	94.47	2.66	48.36	18.2
R4 Std. Dev.				0.12				

RUN #3 DATA

Particle Density - Pycronometer Method - precomposted Date: April 14, 1998

Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	35	124.86	150.14	257.83	256.79	1.12
R1	T	189.72	244.99	494.70	492.23	1.13
R1 Mean						1.12
R1 Std. Dev.						0.01
R2	C	102.59	128.60	226.78	225.85	1.10
R2	A	120.75	159.96	373.89	372.82	1.07
R2 Mean						1.08
R2 Std. Dev.						0.02
R3	A	120.75	167.92	375.33	372.91	1.15
R3	C	102.60	126.38	227.35	225.85	1.19
R3 Mean						1.17
R3 Std. Dev.						0.03
R4	T	189.72	232.86	494.25	492.23	1.13
R4	35	124.87	153.69	257.99	256.72	1.12
R4 Mean						1.13
R4 Std. Dev.						0.01

RUN #3 DATA

Bulk Density - Core Method - precomposted				Date: April 15, 1998								
Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	T	175.49	271.26	212.06	295	250	0.32	0.15	1.12	0.87	0.09	0.78
R1	A1	177.66	279.90	216.68	310	255	0.33	0.15	1.13	0.86	0.09	0.77
R1 Mean							0.33	0.15	1.12	0.87	0.09	0.77
R1 Std. Dev.							0.00	0.00	0.01	0.00	0.00	0.01
R2	B	169.67	272.29	209.45	305	275	0.34	0.14	1.10	0.87	0.09	0.78
R2	K	165.13	263.90	204.62	300	245	0.33	0.16	1.07	0.85	0.10	0.75
R2 Mean							0.33	0.15	1.09	0.86	0.09	0.77
R2 Std. Dev.							0.01	0.01	0.02	0.01	0.01	0.02
R3	E	170.16	268.40	207.97	310	255	0.32	0.15	1.15	0.87	0.09	0.78
R3	F	171.67	278.11	213.40	325	260	0.33	0.16	1.19	0.87	0.10	0.77
R3 Mean							0.32	0.15	1.17	0.87	0.09	0.77
R3 Std. Dev.							0.01	0.01	0.03	0.00	0.01	0.01
R4	Q	171.55	274.22	211.92	320	255	0.32	0.16	1.13	0.86	0.10	0.76
R4	10	174.93	286.56	218.65	340	285	0.33	0.15	1.12	0.86	0.09	0.77
R4 Mean							0.32	0.16	1.13	0.86	0.09	0.77
R4 Std. Dev.							0.01	0.00	0.01	0.00	0.00	0.00

RUN #3 DATA

Run #4 started April 9, 1998 @ 10:00 am

Reactors aerated at a flow rate of approximately 15 mL/sec for 5 min every hour

At time zero, the thermostat on the chamber was set to an initial temp of 35°C.

Compaction Data

Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	R1 (cm)	R2 (cm)	R3 (cm)	R4 (cm)
April	9	10:00	0.0	0.00	25.0	25.0	25.0	25.0
	9	10:30	0.5	0.02	14.8	15.0	15.1	15.1
	9	11:30	1.5	0.06	13.8	14.3	14.6	14.8
	9	13:00	3.5	0.15	13.8	14.0	14.1	14.0
	10	12:30	26.5	1.10	13.6	13.4	13.6	13.5
	11	13:00	51.0	2.13	13.4	13.2	13.3	13.3
	12	12:30	74.5	3.10	13.0	12.9	12.9	12.9
	13	11:00	97.0	4.04	12.8	12.6	12.7	12.7
	13	16:00	102.0	4.25	12.5	12.3	12.5	12.4
	14	11:00	121.0	5.04	12.4	12.1	12.3	12.1
	14	16:00	126.0	5.25	12.2	12.0	12.1	12.0
	15	9:00	143.0	5.96	12.2	11.5	11.7	12.0
	15	16:00	150.0	6.25	12.2	11.4	11.4	12.0
	16	9:00	167.0	6.96	12.1	11.3	11.2	11.9
	16	16:00	174.0	7.25	12.0	11.3	11.2	11.6
	17	11:00	193.0	8.04	12.0	11.2	11.1	11.3
	17	16:00	198.0	8.25	11.9	11.1	11.0	11.2
	18	12:00	218.0	9.08	11.8	11.1	11.0	11.2
	19	14:00	244.0	10.17	11.8	11.1	11.0	11.2
	20	11:00	265.0	11.04	11.6	11.0	10.9	11.2
	20	18:00	270.0	11.25	11.6	11.0	10.9	11.1
	21	10:00	288.0	12.00	11.6	11.0	10.9	11.1
	21	16:00	294.0	12.25	11.5	11.0	10.9	11.1
	22	10:00	312.0	13.00	11.4	11.0	10.8	11.1
	22	16:00	318.0	13.25	11.3	11.0	10.8	11.1
	23	10:00	336.0	14.00	11.3	11.0	10.8	11.1
	23	16:00	342.0	14.25	11.2	11.0	10.8	11.0
	24	11:00	361.0	15.04	11.2	11.0	10.7	11.0
	24	16:00	366.0	15.25	11.2	11.0	10.7	11.0
	25	15:30	389.5	16.23	11.2	11.0	10.7	11.0
	26	14:30	412.5	17.19	11.1	11.0	10.7	10.9
	27	10:30	432.5	18.02	11.1	11.0	10.7	10.9

RUN #3 DATA

Temperature Data									
Month	Day	Time	Elapsed Time (hrs)	Elapsed Time (days)	Chamber (°C)	R1 (°C)	R2 (°C)	R3 (°C)	R4 (°C)
April	9	10:00	0.0	0.00	25.0	25.0	25.0	25.0	25.0
	10	12:30	26.5	1.10	35.0	36.6	36.7	37.5	37.4
	11	13:00	51.0	2.13	37.3	39.1	39.0	40.6	40.8
	12	12:30	74.5	3.10	40.1	43.4	42.1	43.3	43.1
	13	11:00	97.0	4.04	43.5	45.3	46.1	46.4	45.3
	13	16:00	102.0	4.25	45.2	45.9	46.7	47.1	45.9
	14	11:00	121.0	5.04	46.9	47.5	49.2	50.0	48.5
	14	16:00	126.0	5.25	47.5	47.8	49.4	50.2	48.6
	15	9:00	143.0	5.96	48.6	49.0	50.6	52.0	51.0
	15	16:00	150.0	6.25	48.9	49.4	50.8	52.2	51.3
	16	9:00	167.0	6.96	49.3	49.6	50.9	52.3	52.3
	16	16:00	174.0	7.25	49.6	49.7	51.1	52.7	53.1
	17	11:00	193.0	8.04	49.1	49.3	50.8	51.8	52.7
	17	16:00	198.0	8.25	48.0	48.2	49.7	50.8	51.7
	18	12:00	218.0	9.08	46.9	47.1	48.5	49.3	50.1
	19	14:00	244.0	10.17	44.9	45.2	46.6	47.1	47.6
	20	11:00	265.0	11.04	44.0	44.1	45.2	45.7	46.2
	20	18:00	270.0	11.25	43.0	43.1	44.2	44.8	45.3
	21	10:00	288.0	12.00	42.0	42.4	43.5	43.8	44.2
	21	16:00	294.0	12.25	41.5	41.8	42.7	43.1	43.5
	22	10:00	312.0	13.00	40.8	40.9	41.6	41.9	42.3
	22	16:00	318.0	13.25	40.0	40.3	40.8	41.2	41.7
	23	10:00	336.0	14.00	38.4	38.8	39.4	39.6	40.0
	23	16:00	342.0	14.25	38.0	38.4	38.8	39.0	39.4
	24	11:00	361.0	15.04	37.0	37.5	38.0	38.1	38.5
	24	16:00	366.0	15.25	37.0	37.3	37.7	37.9	38.2
	25	15:30	389.5	16.23	35.7	36.0	36.2	36.4	36.6
	26	14:30	412.5	17.19	35.0	34.6	35.1	35.2	35.3
	27	10:30	432.5	18.02	35.0		34.5	34.7	34.9

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RUN #3 DATA

Physical Analysis for Loading Effect on FAS of Composting Mixture - 12 kg load				
Time (days)	R1 FAS (cm³/cm³)	R2 FAS (cm³/cm³)	R3 FAS (cm³/cm³)	R4 FAS (cm³/cm³)
0.00	0.77	0.77	0.77	0.77
0.02	0.37	0.34	0.38	0.34
0.06	0.33	0.31	0.36	0.33
0.15	0.33	0.30	0.34	0.30
1.10	0.32	0.28	0.32	0.28
2.13	0.32	0.27	0.31	0.27
3.10	0.30	0.26	0.30	0.26
4.04	0.29	0.24	0.29	0.25
4.25	0.28	0.23	0.28	0.24
5.04	0.28	0.22	0.27	0.22
5.25	0.27	0.22	0.26	0.22
5.96	0.27	0.20	0.25	0.22
6.25	0.27	0.20	0.24	0.22
6.96	0.26	0.19	0.23	0.22
7.25	0.26	0.19	0.23	0.20
8.04	0.26	0.19	0.22	0.19
8.25	0.26	0.18	0.22	0.19
9.08	0.25	0.18	0.22	0.19
10.17	0.25	0.18	0.22	0.19
11.04	0.24	0.18	0.22	0.19
11.25	0.24	0.18	0.22	0.18
12.00	0.24	0.18	0.22	0.18
12.25	0.24	0.18	0.22	0.18
13.00	0.24	0.18	0.21	0.18
13.25	0.23	0.18	0.21	0.18
14.00	0.23	0.18	0.21	0.18
14.25	0.23	0.18	0.21	0.18
15.04	0.23	0.18	0.21	0.18
15.25	0.23	0.18	0.21	0.18
16.23			0.21	0.18
17.19			0.21	0.18

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RUN #3 DATA

Solids Data - composted			Date: April 27, 1998							
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC^A (%db)
R1	45	83.19	103.86	90.82	84.38	36.91	63.09	84.40	15.60	46.89
R1	23	90.56	110.17	97.63	91.72	36.05	63.95	83.59	16.41	46.44
R1	25	92.17	115.89	100.77	93.51	36.26	63.74	84.42	15.58	46.90
R1	47	84.10	101.09	90.28	85.06	36.37	63.63	84.47	15.53	46.93
R1 Mean						36.40	63.60	84.22	15.78	46.79
R1 Std. Dev.						0.37	0.37	0.42	0.42	0.23
R2	43	83.78	104.69	91.63	84.91	37.54	62.46	85.61	14.39	47.56
R2	30	94.16	113.87	101.59	95.26	37.70	62.30	85.20	14.80	47.33
R2	51	80.98	103.05	89.32	82.17	37.79	62.21	85.73	14.27	47.63
R2	3	90.94	114.86	99.76	92.22	36.87	63.13	85.49	14.51	47.49
R2 Mean						37.48	62.52	85.50	14.50	47.50
R2 Std. Dev.						0.41	0.41	0.23	0.23	0.13
R3	J-15	71.63	88.96	78.00	72.64	36.76	63.24	84.14	15.86	46.75
R3	35	92.65	113.62	100.24	93.88	36.19	63.81	83.79	16.21	46.55
R3	7	85.71	105.62	92.82	86.77	35.71	64.29	85.09	14.91	47.27
R3	27	96.82	116.07	103.84	97.89	36.47	63.53	84.76	15.24	47.09
R3 Mean						36.28	63.72	84.45	15.55	46.92
R3 Std. Dev.						0.45	0.45	0.59	0.59	0.33
R4	111	91.30	110.95	98.44	92.48	36.34	63.66	83.47	16.53	46.37
R4	57	91.62	110.87	98.49	92.75	35.69	64.31	83.55	16.45	46.42
R4	118	103.92	122.25	110.60	105.01	36.44	63.56	83.68	16.32	46.49
R4	J-12	87.12	106.62	94.17	88.29	36.15	63.85	83.40	16.60	46.34
R4 Mean						36.16	63.84	83.53	16.47	46.40
R4 Std. Dev.						0.33	0.33	0.12	0.12	0.07

^A OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Haug 1993, Liao 1995), where OC and FS are based on the dry weight fraction

RUN #3 DATA

TKN Prepared Samples Solids Data - composted						Date: May 4, 1998				
Reactor	Crucible #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	After 550°C (g)	% TS (%wb)	% MC (%wb)	% VS (%db)	% FS (%db)	% OC* (%db)
R1	30	94.17	101.72	101.11	95.13	91.92	8.08	86.17	13.83	47.87
R1	118	103.92	111.94	111.30	104.95	92.02	7.98	86.04	13.96	47.80
R1	J-12	87.12	96.37	95.61	88.30	91.78	8.22	86.10	13.90	47.83
R1	25	92.17	101.26	100.52	93.31	91.86	8.14	86.35	13.65	47.97
R1 Mean						91.90	8.10	86.16	13.84	47.87
R1 Std. Dev.						0.10	0.10	0.13	0.13	0.07
R2	J-15	71.63	78.54	77.97	72.51	91.75	8.25	86.12	13.88	47.84
R2	45	83.20	92.77	92.00	84.44	91.95	8.05	85.91	14.09	47.73
R2	43	83.77	93.15	92.39	84.99	91.90	8.10	85.85	14.15	47.69
R2	111	81.30	99.65	96.97	92.37	91.86	8.14	86.05	13.95	47.81
R2 Mean						91.86	8.14	85.98	14.02	47.77
R2 Std. Dev.						0.09	0.09	0.13	0.13	0.07
R3	47	84.10	91.14	90.61	85.09	92.47	7.53	84.79	15.21	47.11
R3	27	96.82	105.51	104.87	96.04	92.64	7.36	84.84	15.16	47.14
R3	35	92.66	101.43	100.77	93.89	92.47	7.53	84.83	15.17	47.13
R3	23	90.56	98.88	98.24	91.71	92.31	7.69	85.03	14.97	47.24
R3 Mean						92.47	7.53	84.87	15.13	47.15
R3 Std. Dev.						0.13	0.13	0.10	0.10	0.06
R4	51	80.99	90.86	90.07	82.29	92.00	8.00	85.68	14.32	47.60
R4	3	90.94	101.30	100.48	92.34	92.08	7.92	85.32	14.68	47.40
R4	7	85.71	93.86	93.22	86.75	92.15	7.85	86.15	13.85	47.86
R4	57	91.60	100.36	99.66	92.74	92.01	7.99	85.86	14.14	47.70
R4 Mean						92.06	7.94	85.75	14.25	47.64
R4 Std. Dev.						0.07	0.07	0.35	0.35	0.19

* OC (Organic Carbon) calculated using the following equation: OC = (1-FS)/1.8 (Heug 1993, Liao 1993), where OC and FS are based on the dry weight fraction

RUN #3 DATA

TKN Data - composted			Date: May 7, 1998					
Sample	Sample Weight (g)	Units on Graph	Concentration of N (mg/L)	% N (%wb)	% TS (%wb)	% N (%db)	% C (%db)	C/N
Blank		4.5						
Blank		4.5						
Blank Mean		4.500						
Standard		10	5.00					
Standard		17	10.00					
Standard		35.5	25.00					
Standard		62.50	50.00					
R1	0.1	16.5	10	0.50				
R1	0.1	16	9.5	0.48				
R1	0.1	16	9.5	0.48				
R1	0.1	15.5	9	0.45				
R1 Mean				0.48	91.90	0.51	47.87	83.2
R1 Std. Dev.				0.02				
R2	0.1	27.5	19.5	0.98				
R2	0.1	28	20	1.00				
R2	0.1	27.5	19.5	0.98				
R2	0.1	29	20.5	1.03				
R2 Mean				0.99	91.86	1.07	47.77	44.5
R2 Std. Dev.				0.02				
R3	0.1	44	34.5	1.73				
R3	0.1	40.5	30.5	1.53				
R3	0.1	44	34.5	1.73				
R3	0.1	38	28.5	1.43				
R3 Mean				1.60	92.47	1.72	47.15	27.4
R3 Std. Dev.				0.15				
R4	0.1	67.5	53.5	2.68				
R4	0.1	65	51.5	2.58				
R4	0.1	65	51.5	2.58				
R4	0.1	63	49.5	2.48				
R4 Mean				2.58	92.06	2.78	47.64	17.1
R4 Std. Dev.				0.08				

RUN #3 DATA

Particle Density - Pycnometer Method - composted   Date: April 29, 1998
Temperature = 20°C, Density of H2O (@20°C) = 0.998 g/cm³

Reactor	Flask #	Tare (g)	Tare + Feedstock (g)	Tare + Feedstock + H2O (g)	Tare + H2O (g)	Dry Particle Density (g/cm³)
R1	A	120.75	168.11	377.93	374.25	1.27
R1	35	124.87	156.91	259.79	257.89	1.19
R1 Mean						1.23
R1 Std. Dev.						0.05
R2	35	124.87	156.18	259.22	256.77	1.26
R2	T	189.73	244.45	496.79	492.08	1.30
R2 Mean						1.28
R2 Std. Dev.						0.02
R3	C	102.59	132.28	229.65	226.87	1.35
R3	A	120.75	167.6	378.43	374.14	1.33
R3 Mean						1.34
R3 Std. Dev.						0.01
R4	T	189.72	244.68	499.26	494.44	1.32
R4	C	102.59	125.69	228.70	225.8	1.53
R4 Mean						1.42
R4 Std. Dev.						0.15

Bulk Density - Core Method - composted   Date: April 28, 1998

Reactor	Beaker #	Tare (g)	Tare + Feedstock (g)	After 103°C (g)	Wet Volume (cm³)	Dry Volume (cm³)	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Dry Particle Density (g/cm³)	Porosity (mL/mL)	Vol. Water Content (mL/mL)	FAS (mL/mL)
R1	G	174.92	287.59	215.95	275	250	0.41	0.16	1.27	0.87	0.10	0.77
R1	T	163.45	271.61	203.30	260	240	0.42	0.17	1.19	0.86	0.11	0.75
R1 Mean							0.41	0.17	1.23	0.87	0.11	0.76
R1 Std. Dev.							0.00	0.00	0.05	0.01	0.00	0.01
R2	D	168.23	289.53	212.65	280	250	0.43	0.18	1.26	0.86	0.11	0.75
R2	3	169.13	291.63	214.67	285	240	0.43	0.19	1.30	0.85	0.12	0.73
R2 Mean							0.43	0.18	1.28	0.86	0.12	0.74
R2 Std. Dev.							0.00	0.01	0.02	0.00	0.01	0.01
R3	10	174.93	296.78	219.84	275	240	0.44	0.19	1.35	0.86	0.12	0.74
R3	1	170.16	292.85	214.84	280	230	0.44	0.19	1.33	0.85	0.12	0.73
R3 Mean							0.44	0.19	1.34	0.86	0.12	0.74
R3 Std. Dev.							0.00	0.01	0.01	0.00	0.00	0.01
R4	2	167.25	285.31	210.20	275	230	0.43	0.19	1.32	0.86	0.12	0.74
R4	K	171.77	298.63	217.87	275	250	0.46	0.18	1.53	0.88	0.12	0.76
R4 Mean							0.45	0.19	1.42	0.87	0.12	0.75
R4 Std. Dev.							0.02	0.00	0.15	0.01	0.00	0.02

RUN #3 DATA

Volatile Solids Reduction

Reactor	Feedstock Weight (g)	Feedstock MC (%wb)	Feedstock %VS (%db)	Total Feedstock VS (g)	Compost Weight (g)	Compost MC (%wb)	Compost VS% (%db)	Total Compost VS (g)	VS % Reduction (%)	AVS/VI (%/day)
R1	726.4	61.56	87.03	243.0	703.5	63.60	84.40	216.13	11.05	0.65
R1	726.4	61.56	85.30	238.2	703.5	63.60	83.59	214.05	10.12	0.60
R1	726.4	61.56	87.66	244.8	703.5	63.60	84.42	216.17	11.68	0.69
R1	726.4	61.56	87.50	244.3	703.5	63.60	84.47	216.29	11.46	0.68
R1 Mean									11.08	0.65
R1 Std. Dev.									0.69	0.04
R2	730.3	60.78	86.50	247.8	679.1	62.52	85.61	217.86	12.07	0.70
R2	730.3	60.78	89.06	255.1	679.1	62.52	85.20	216.82	15.00	0.87
R2	730.3	60.78	87.03	249.3	679.1	62.52	85.73	218.18	12.48	0.72
R2	730.3	60.78	85.92	246.1	679.1	62.52	85.49	217.56	11.59	0.67
R2 Mean									12.78	0.74
R2 Std Dev									1.52	0.09
R3	736.1	60.93	86.81	249.7	711.2	63.72	84.14	217.13	13.03	0.74
R3	736.1	60.93	89.21	256.6	711.2	63.72	83.79	216.22	15.72	0.90
R3	736.1	60.93	87.72	252.3	711.2	63.72	85.09	219.57	12.97	0.74
R3	736.1	60.93	86.86	249.8	711.2	63.72	84.76	218.71	12.44	0.71
R3 Mean									13.54	0.77
R3 Std Dev.									1.48	0.08
R4	743.4	60.58	86.56	253.6	707.5	63.84	83.47	213.52	15.81	0.88
R4	743.4	60.58	86.46	253.3	707.5	63.84	83.55	213.72	15.64	0.87
R4	743.4	60.58	86.74	254.2	707.5	63.84	83.68	214.06	15.78	0.88
R4	743.4	60.58	87.52	256.4	707.5	63.84	83.40	213.35	16.80	0.94
R4 Mean									16.01	0.88
R4 Std. Dev.									0.53	0.03

Particle Size Distribution   Date: May 11, 1998

Sample	>1/4"(g)	1/8-1/4"(g)	<1/8"(g)	>1/4"(%)	1/8-1/4"(%)	<1/8"(%)
R0	113.72	43.87	10.84	67.52	26.05	6.44
R1	87.53	80.8	31.72	43.75	40.39	15.86
R2	76.91	61.71	19.86	48.53	38.94	12.53
R3	74.69	87.03	26.68	44.35	39.80	15.84
R4	73.07	66.88	31.07	42.73	39.11	18.17

Run #3

Compaction Results (12kg load)

Legend:
- R1 (cm)
- R2 (cm)
- R3 (cm)
- R4 (cm)

X-axis: Time (days)
Y-axis: Height (cm)
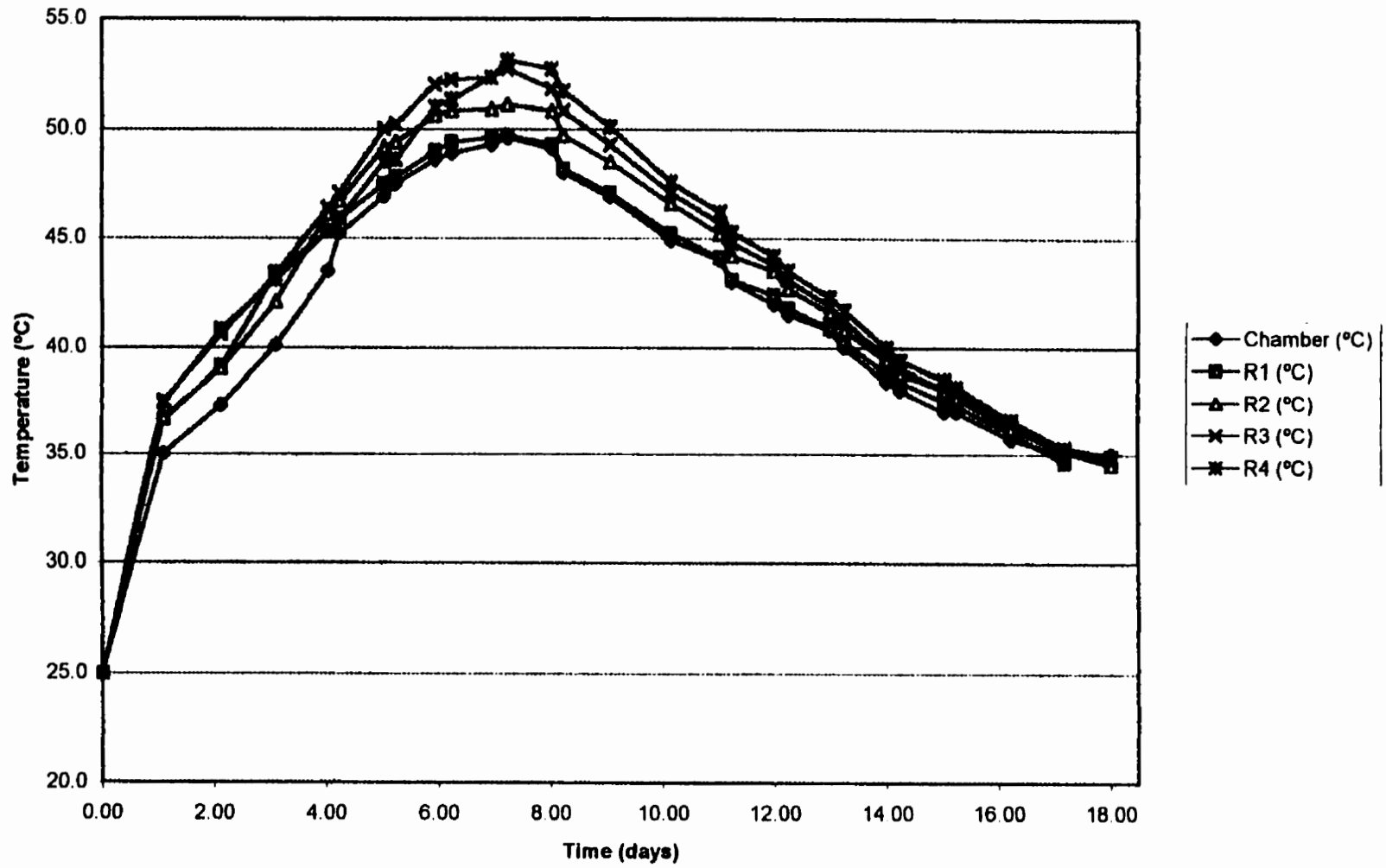
Run #3

Free Air Space Results (12 kg load)

221
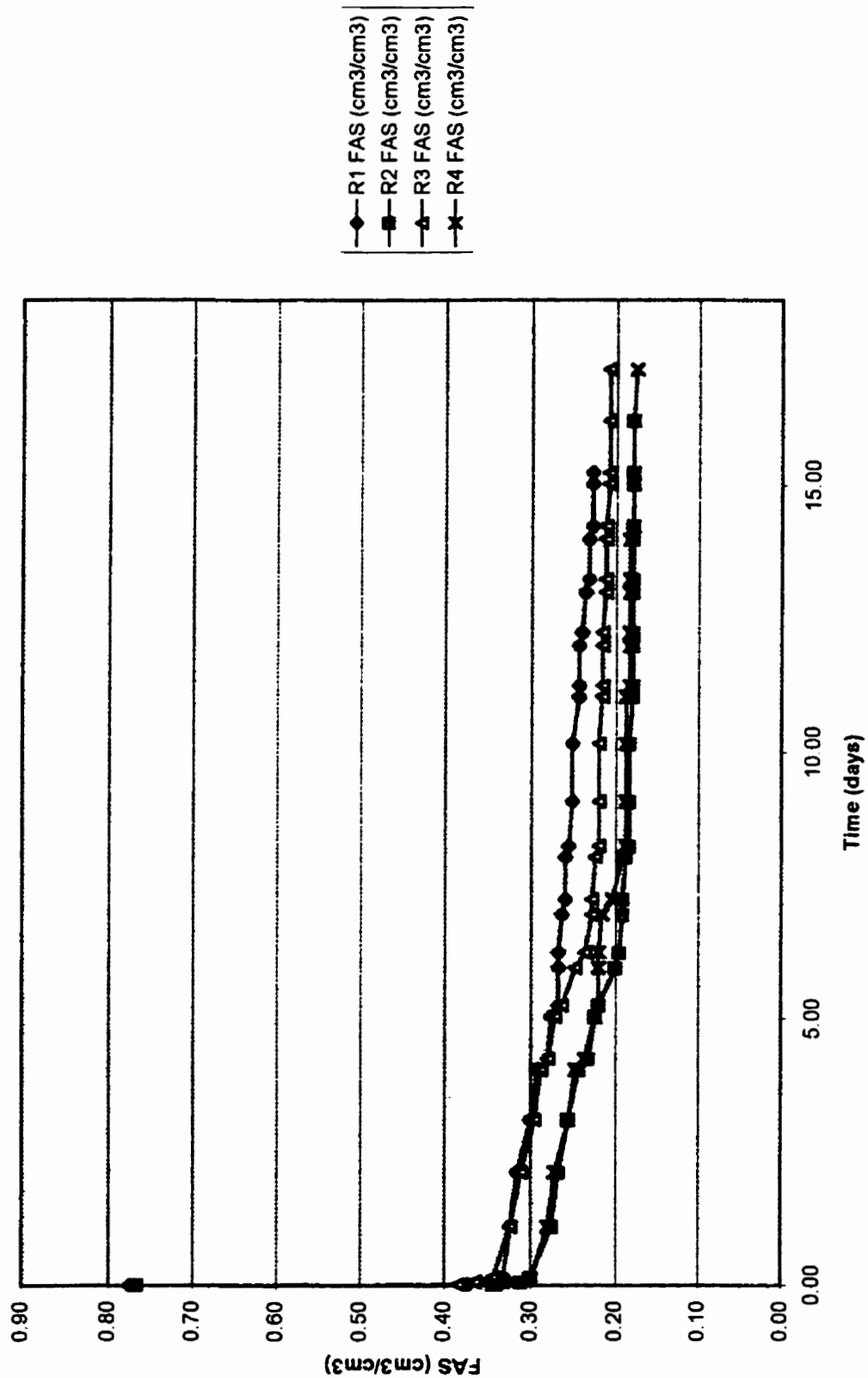
Run #3

Temperature Rusults (Run #3)

Run #3

Volatile Solids Reduction - Run #3

Legend:
- 90:1
- 50:1
- 30:1
- 20:1

Y-axis: VS Reduction (%)
Y-axis values: 20.00, 18.00, 16.00, 14.00, 12.00, 10.00, 8.00, 6.00, 4.00, 2.00, 0.00

X-axis: C:N Ratio
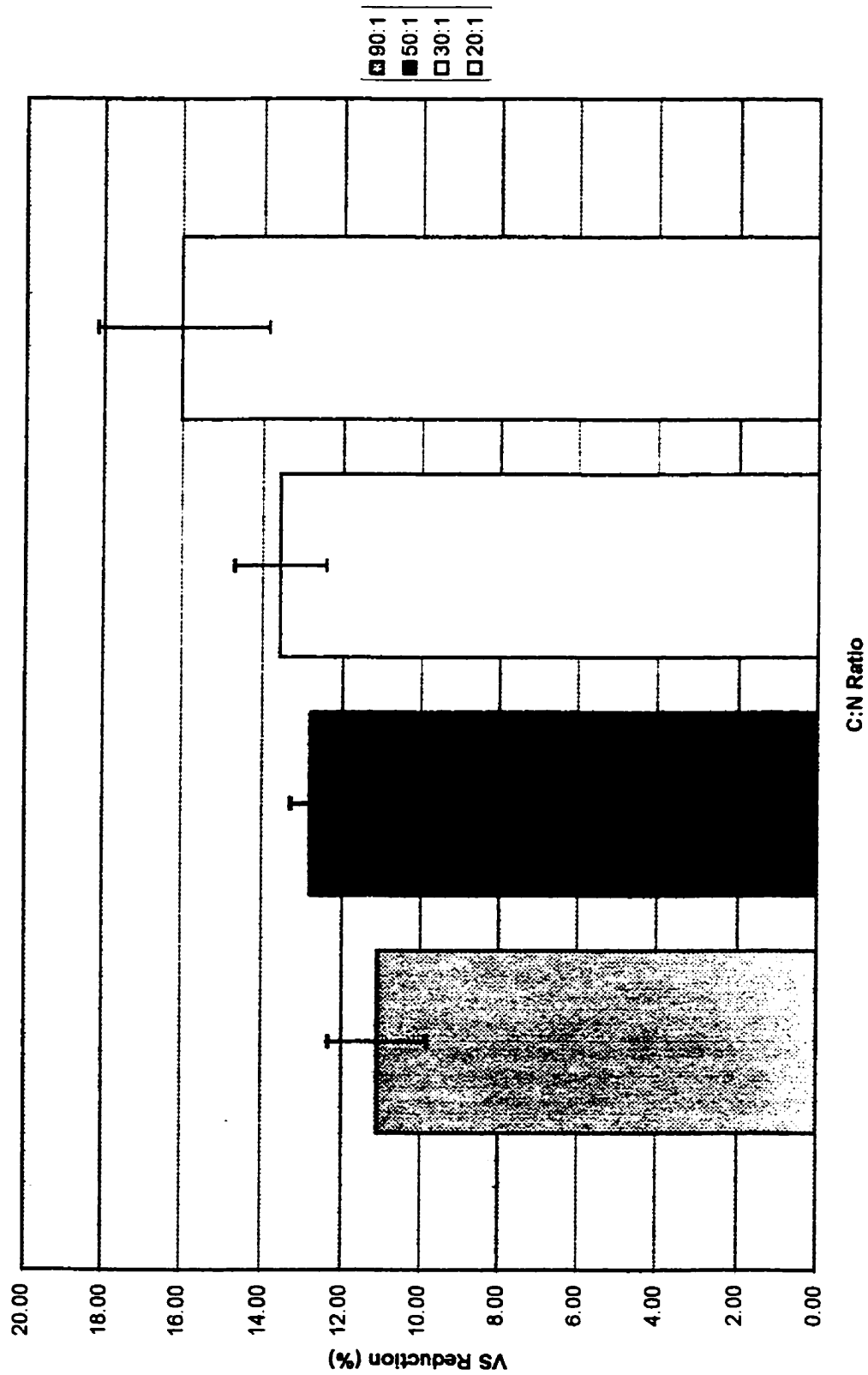
FERTILIZER TKN DATA

Standard curve

Conc	Peak ht
0	0
1	1.05
5	3
10	5.7
25	11.7
50	20.4

Sample ID	Peak ht	(mg/l)	dil	mg/l Dil	TKN wt (g)	Sample wt (g)	%TKN	Average
bl	1.3	1.026414						
1a	15.7	36.90979	20	738.1959	0.03691	0.1021	36.15063	31.14201
1b	16.35	38.52953	20	770.5906	0.03853	0.1215	31.71155	
2a	11.9	27.44057	50	1372.028	0.068601	0.2022	33.92751	
2b	12.1	27.93895	50	1396.947	0.069847	0.2421	28.85063	
5a	18.65	44.2609	80	3540.872	0.177044	0.5068	34.93362	
5b	20.45	48.74632	80	3899.706	0.194985	0.5169	37.72205	
5c	14.9	34.91627	80	2793.302	0.139665	0.5053	27.64003	
5d	12.6	29.1849	80	2334.792	0.11674	0.503	23.20867	

Corrected Standard curve

Conc	Peak ht
0	0
5	1.7
10	4.4
25	10.4
50	19.1

Sample ID	Peak ht	(mg/l)	dil	mg/l Dil	TKN wt (g)	Sample wt (g)	%TKN	Average
bl	0	-0.5186						
1a	14.4	36.93264	20	738.6528	0.036933	0.1021	36.17301	31.085
1b	15.05	38.62315	20	772.4629	0.038623	0.1215	31.7886	
2a	10.6	27.04967	50	1352.484	0.067624	0.2022	33.44421	
2b	10.8	27.56983	50	1378.492	0.068925	0.2421	28.46947	
5a	17.35	44.60494	80	3568.395	0.17842	0.5068	35.20516	
5b	19.15	49.28635	80	3942.908	0.197145	0.5169	38.13995	
5c	13.6	34.85202	80	2788.161	0.139408	0.5053	27.58917	
5d	11.3	28.87022	80	2309.618	0.115481	0.503	22.95843	

std curve

Standard curve for TKN analysis

$y = 0.4013x + 0.8881$
$R^2 = 0.9921$

Conc (mg/l)

Peak height (cms)
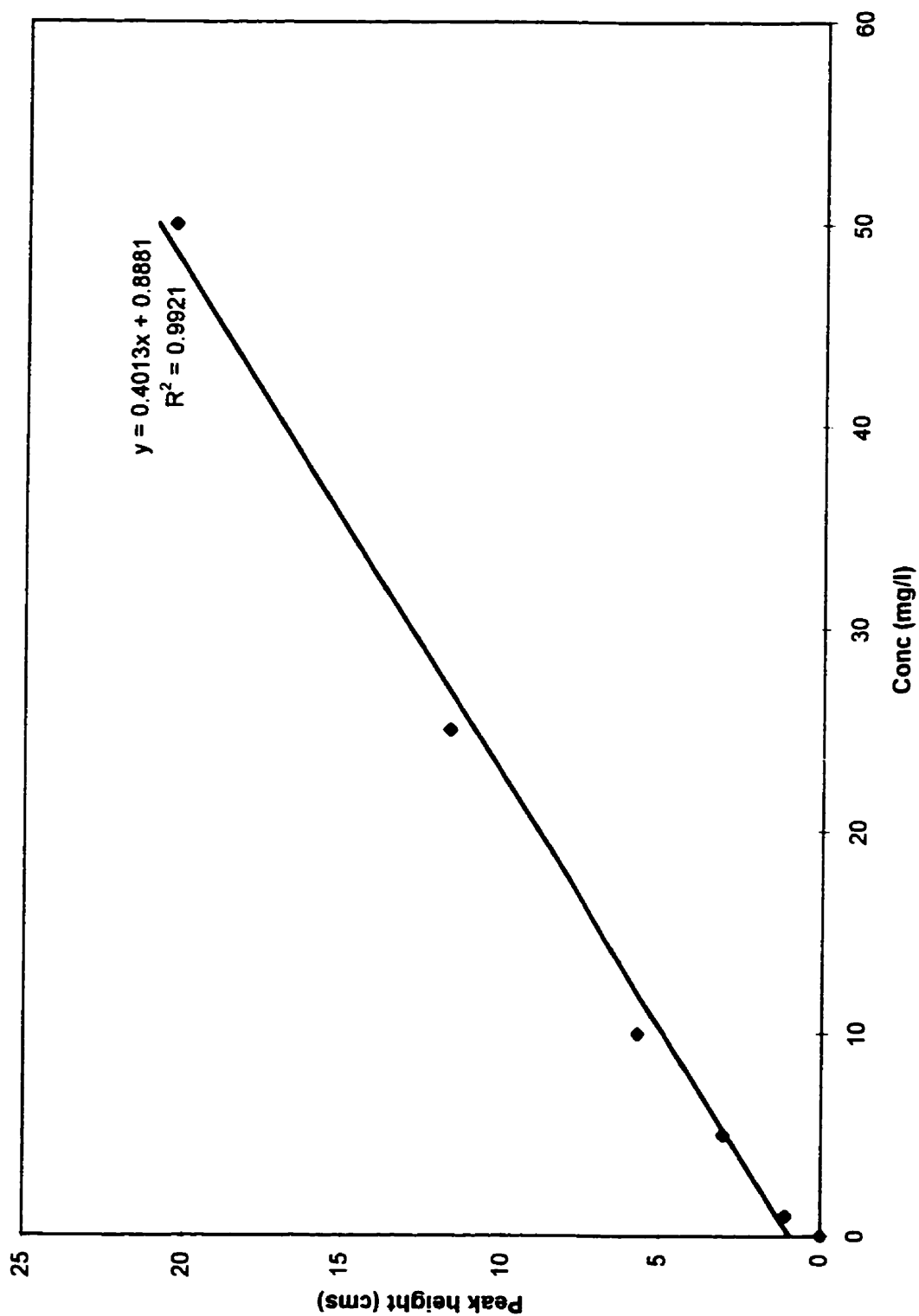
Corr std curve

Standard curve for TKN analysis

$y = 0.3845x + 0.1994$
$R^2 = 0.9967$

Conc (mg/l)

Peak ht (cms)
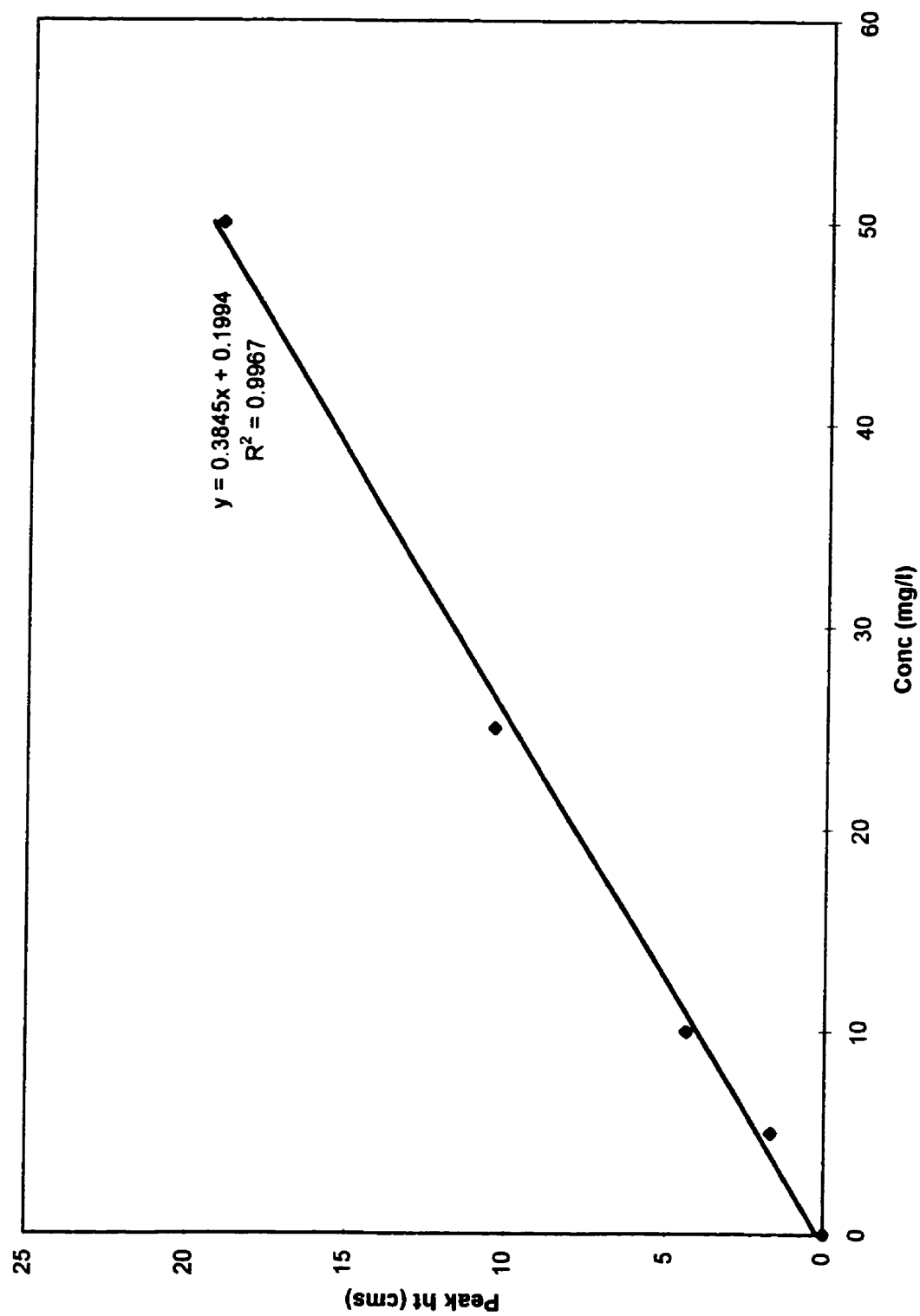
APPENDIX E – REACTOR AIR REQUIREMENTS

Assume:

Estimation of Chemical Composition
Ultimate analysis values estimated from
Enter % values for C, H, O, N, S, and Ash

Scott and Smith 1995
* for 0.75 kg bark/kg biosolids

Component	%
Carbon	38.2
Hydrogen	5.1
Oxygen	35.2
Nitrogen	0.5
Sulfur	0.2
Ash	9.5

Compute the molar composition of the elements neglecting ash
Assume a total of 100 grams of biosolids

Component	At. Wt. (gm/mol)	Moles
Carbon	12.01	3.19
Hydrogen	1.01	5.05
Oxygen	16.00	2.20
Nitrogen	14.01	0.04
Sulfur	32.07	0.01

Determine the normalized mole ratios

Component	Mole Ratio (S=1)
Carbon	511.4
Hydrogen	809.7
Oxygen	352.8
Nitrogen	5.7
Sulfur	1.0

Write Chemical Formula using mole ratios
$C_{511}H_{810}O_{353}N_6S$

- Composition of waste is given by $C_{415}H_{699}O_{302}N_{10}$
- Moisture content of organic fraction of feedstock = 60%
- Volatile Solids, VS = 0.87 X TS (total solids)
- Biodegradable volatile solids, BVS = 0.60 X VS
- Expected BVS conversion efficiency = 95%
- Composting time = 17 days
- The ammonia produced during the aerobic decomposition of the waste is lost to the atmosphere.

- Air contains 23% O_2 by mass, and the specific weight of air is equal 1.215 kg/m^3
- A factor of 2 times the actual air supplied will be needed to be assured that the oxygen content of the air does not drop below 50 percent of its original value.
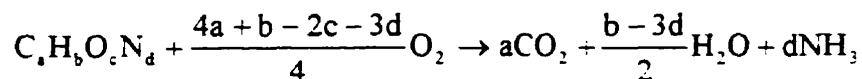
1) Mass of biodegradable volatile solids

Mass BVS $= 0.9722 \text{ kg} \times 0.4 \times 0.87 \times 0.60 = 0.203 \text{ kg}$

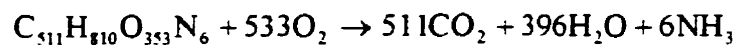2) Expected BVS conversion

Expected BVS conversion $= 0.203 \text{kg} \times 0.95 = 0.193 \text{ kg}$

3) Oxygen required for the decomposition of one kg of the biodegradable volatile solids using the following equation:

$$C_a H_b O_c N_d + \frac{4a + b - 2c - 3d}{4} O_2 \rightarrow aCO_2 + \frac{b - 3d}{2} H_2O + dNH_3$$

The balanced equation is:

$$C_{511} H_{810} O_{353} N_6 + 533 O_2 \rightarrow 511 CO_2 + 396 H_2O + 6NH_3$$

O_2 required $= 17056 \text{ kg } O_2 / 12674 \text{ kg BVS converted}$

$= 1.35 \text{ kg } O_2 / \text{kg BVS converted}$

4) Total amount of air required for 0.9722 kg of feedstock, containing 0.193 kg of BVS

$$\text{Air Required} = \frac{0.193 \text{ kg BVS} \times \dfrac{1.35 \text{ kg } O_2}{\text{kg BVS converted}}}{\dfrac{0.23 \text{ kg } O_2}{\text{kg air}} \times \dfrac{1.215 \text{ kg air}}{\text{m}^3 \text{ air}}} = 0.93 \text{ m}^3 \text{ air}$$

5) Safety factor so that the oxygen content of the air does not drop below 50 percent of its original value.

Air Required $= 0.93 \, m^3 \times 2 = 1.86 \, m^3$ air $= 1860$ Litres air

6) Air required per hour

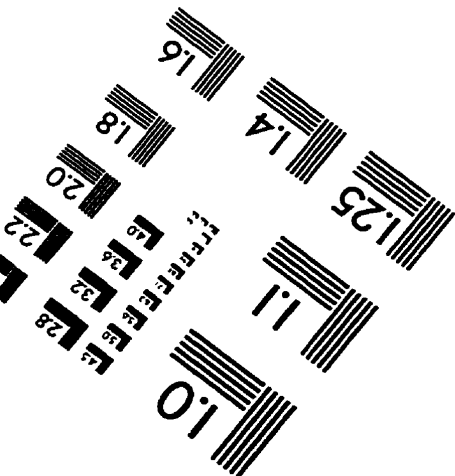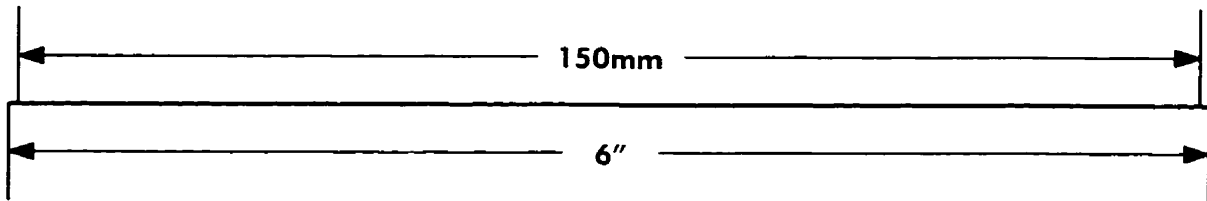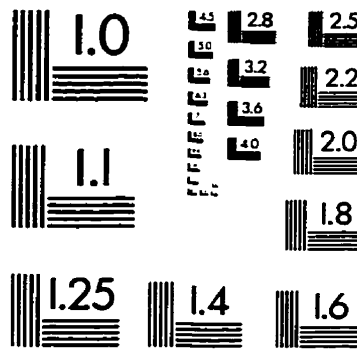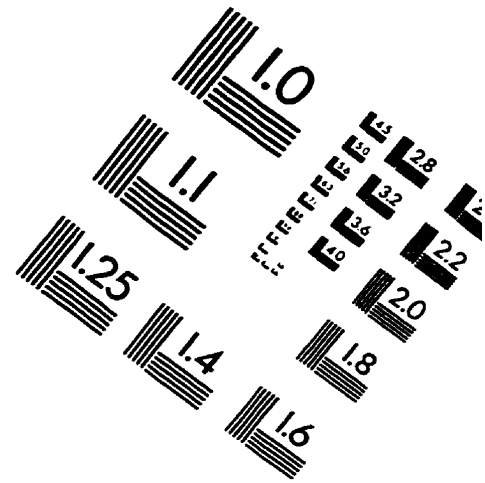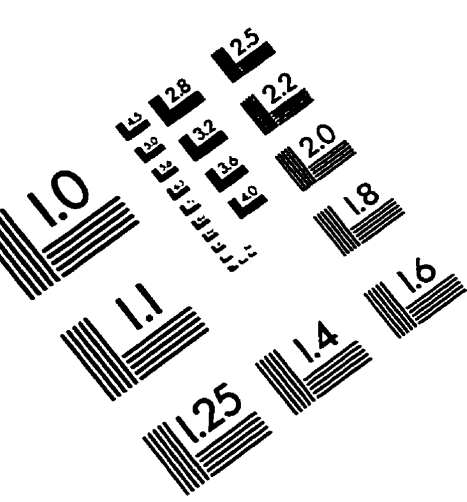$$\text{Air Required} = \frac{1860 \, L}{17 \, days} \times \frac{1 \, day}{24 \, hours} = 4.56 L/hour$$

7) If air is supplied for 5 minute intervals each hour

$$\text{Air Required} = \frac{4.56 \, L}{hour} \times \frac{1 \, hour}{5 \, minutes} = 0.912 \, L/min$$

$$\text{Air Required} = \frac{0.912 \, L}{min} \times \frac{1 \, min}{60 \, sec} = 1.5 \times 10^{-2} L/sec$$

$$= 15 \, mL/sec$$

IMAGE EVALUATION
TEST TARGET (QA-3)

150mm

6"