EFFECT OF SOIL LOADING RATE ON MICROBIAL ACTIVITY DURING CO-COMPOSTING OF DIESEL CONTAMINATED CLAY SOIL

By

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A Thesis
Submitted to the Faculty of Graduate Studies
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During Co-composting of Diesel Contaminated Clay Soil

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ABSTRACT

The purpose of this experiment was to determine the effect of soil loading rate on the microbial performance during active phase co-composting of diesel-fuel contaminated clay soil under simulated windrow composting conditions. Microbial performance was monitored through relative heat generation, volatile solids destruction, and headspace oxygen/methane levels. Additional analyses in the form of radio-labelled diesel fuel, which was monitored through NaOH traps for respired $^{14}CO_2$, and total petroleum hydrocarbon (TPH) concentrations were attempted during the experimental run.

A total of seventeen biocells were used during the experiment. Soil loadings ranged from 0% contaminated soil to 30% contaminated soil. Each biocell received the same amount of compost amendments, with altering soil loadings. Biocells were placed in an environmental chamber for a duration of two weeks. During that time, the chamber temperature was ramped to simulate temperatures within a compost heap. Biocell height and temperature readings were taken at least three times daily. Air was supplied to the biocells for five minutes every hour, and the offgas from the biocells was bubbled through NaOH traps to capture respired CO_2 and $^{14}CO_2$.

The results indicate that above 20% contaminated soil loading, the oxygen levels in the headspace of the reactors began to drop. Above 26% soil loading, methane levels were detected within the headspace. These results corresponded to the relative heat generation results, where at soil loadings above 26%, relative heat generation levels dropped sharply. This is further supported by the volatile solids destruction results, which dropped at above 24% soil loading. The decrease in volatile solids is likely due to the decrease in available oxygen and the onset of anaerobic conditions, seen as methane levels in the headspace of the reactors.

Radiolabelled $^{14}CO_2$ was not detected in the trap system, indicating that no radiolabelled diesel fuel was utilized by the microorganisms. The system should be allowed to compost for a longer duration to determine whether the respired $^{14}CO_2$ is generated.

The total petroleum hydrocarbon results performed initially showed that total petroleum hydrocarbon levels in the woodchips are significantly greater than levels in the contaminated clay soil. The total petroleum hydrocarbon concentrations in the woodchips masked the diesel added to the clay soil, as the levels added to the woodchips were significantly higher than present in the clay soil.

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NOMENCLATURE

APHA	American Public Health Association
alicyclic	cyclic non-aromatic hydrocarbon compound
aliphatic	non-aromatic hydrocarbon compound
alkanes	hydrocarbon compounds containing carbon-carbon single bonds
alkenes	hydrocarbon compounds containing carbon-carbon double bonds
aromatic	compounds containing benzene rings (carbon double and single bonds in a ring formation)
BTEX	benzene, toluene, ethyl benzene, xylene components
C:N	carbon to nitrogen ratio
ρ_b	wet bulk density
db	dry basis
DOD	Department of Defense (US)
FAS	free air space, %
feedstock	the inorganic fraction of a co-composting mixture (generally soil)
FS	fixed solids, % of dry weight
MC	moisture content
MOG	mineral oil and grease
NEWPCC	North End Water Pollution Control Centre
NRAES	Northeast Regional Agricultural Engineering Service
organic amendments	the organic fraction of a co-composting mixture
PAH	polycyclic aromatic hydrocarbons
SVOC	Semi-volatile organic compound
TC	carbon content, %
TKN	total Kjeldahl nitrogen
TNT	trinitrotoluene, an explosive
TPH	total petroleum hydrocarbon
TS	total solids, %
VOC	volatile organic compound
VS	volatile solids, %
WW	wastewater
wb	wet basis
ρ_{db}	dry bulk density
ρ_b	bulk density (wet bulk density)
ρ_p	particle density

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1.0 INTRODUCTION

The City of Winnipeg and part of southern Manitoba are underlain by thick clay soil deposits. Many sites in Manitoba are being investigated for diesel fuel contamination. Since polynuclear aromatic hydrocarbon (PAH) concentrations generally increase near urban and industrial centres (Henner et al., 1997), the clay soil underlying the City of Winnipeg has the potential to become hydrocarbon contaminated.

Guidelines for total semi-volatile hydrocarbon cleanup of soils in the province of Manitoba currently specify targets of 2000 mg kg^{-1} for Level II (Medium Risk) and Level III (Low Risk) land usage, and 500 mg kg^{-1} for Level I (High Risk) land usage. Guidelines for volatile hydrocarbons specify targets of 100 mg kg^{-1} for Level I use, 150 mg kg^{-1} for Level II use, and 800 mg kg^{-1} for Level III land use (Manitoba Environment, June 1996).

Presently, two options are available for sites with contaminated clay soils. The first option is natural attenuation, the process of leaving contamination within the soil to allow natural biodegradation to occur. This process is slow and often there is recalcitrant contamination, generally occurring as the heavier hydrocarbons. If natural attenuation is not feasible at a specific site, then an alternative method must be used to remediate the soils to a level acceptable according to the legislation.

Presently, the only other viable option is landfarming the contaminated clays. Landfarming is a slow remediation process due to the strongly sorbed characteristics of the diesel fuel. This process also releases volatiles from the diesel fuels directly into the atmosphere, and rarely achieves low contaminant levels. Landfarming also can slow or stop during the extremely cold temperatures which Manitoba experiences for half of the year. A

possible alternative to landfarming the clay soil would be to use co-composting as a bioremediation technique for the soil.

Co-composting, the process of combining contaminated soil with a compost mixture and allowing it to compost, has the potential to overcome some of the shortcomings of landfarming. Using compost increases the number of microorganisms available to degrade the substrate, and can help to maintain favourable conditions at lower ambient temperatures; this increase in temperature should increase the rate of desorption and biodegradation. Co-composting should increase the amount of diesel fuel remediated, decrease the amount of volatile hydrocarbons reaching the atmosphere, and allow the remediation process to occur at a faster rate than landfarming. Co-composting has been proven as a valuable remediation tool on soils that range from sand and gravel to sandy-silt with minor clay (19%), but heavy clay soil has not been reported in the literature presently published in the co-composting field (Al-Daher et al., 1998; Beaudin et al., 1996; Benoit and Barriuso, 1996; Cho et al., 1997b; Kastner et al., 1995; Liu and Cole, 1995; Valo and Salkinoja-Salonen, 1986).

The purpose of this thesis was to determine the relationship between contaminated heavy clay soil loading rate and microbial co-composting performance. The microbial performance was monitored through volatile solids removal and relative heat generation. The contaminated soil was heavy clay soil from a typical site underlying the City of Winnipeg, and was contaminated with diesel fuel #2 which was spiked with 1-^{14}C-octadecane. The compost mixture was created using biosolids from the City of Winnipeg's North End Water Pollution Control Centre and woodchips created from trees at the University of Manitoba Fort Garry campus.

2.0 WINNIPEG CLAY CHARACTERIZATION

The City of Winnipeg is located mainly on sediments that were deposited approximately 11,700 to 8,500 years ago (Teller 1985). The upper clays and silt materials are of glacio-lacustrine origin, deposited by Lake Agassiz; these soils overlie glacial till and a limestone aquifer (Teller, 1985; Baracos et al., 1979).

2.1 STRATIGRAPHY

Stratigraphy in the Winnipeg area consists of an upper layer of urban fills, mixed with clays, silts and organic soils. This layer ranges from 0.5 to 4.5 m below grade (Baracos et al., 1979; Kjartanson, 1983). The urban fill overlies a silty clay unit, which ranges from 9 to 12 m in depth. The silty clay shows the effects of weathering, with a grey or grey-brown colour due to oxidation from the top 1.5 to 4.5 m of the unit. Below the oxidized clay, the soil becomes unoxidized and is a grey or grey-blue colour, and becomes increasingly soft with depth. Both of the clays (unoxidized and oxidized) have similar mineralogy and clay size fractions (Baracos et al., 1979; Baracos and Graham, 1980). Below the layer of silty clay occurs glacial tills from 3 to 6 m thickness. The tills overlie the bedrock in the region, which is a Paleozoic carbonate bedrock (Baracos et al., 1979). The bedrock contains an aquifer which is an important source of water, used for cooling and industrial purposes (Render, 1970).

The stratigraphy in the Winnipeg area is summarized in Figure 2.1, taken from Baracos et al. (1979):

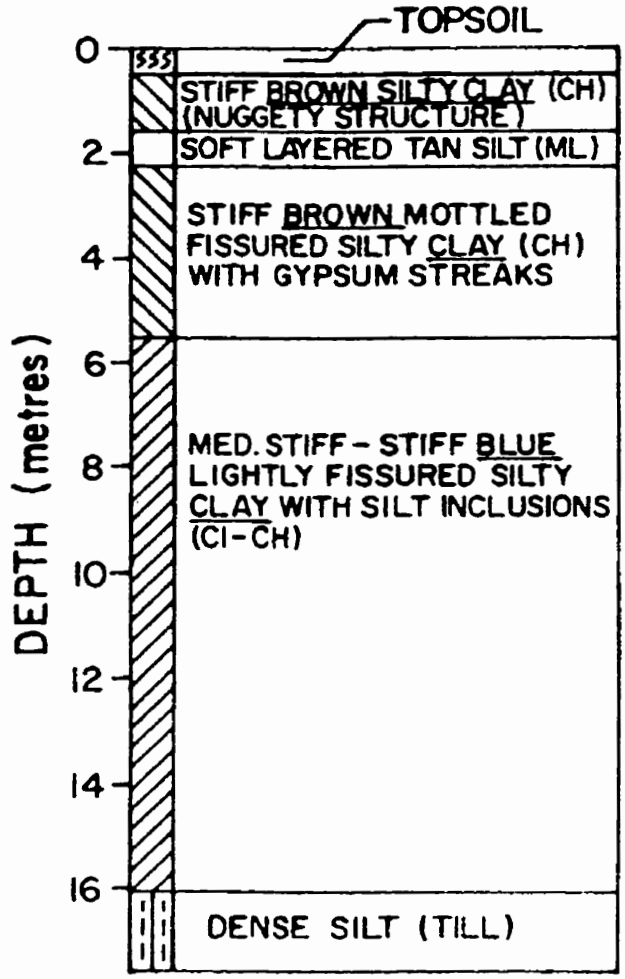

Figure 2.1: Typical Stratigraphic Section showing soil types within the Winnipeg area taken from Baracos et al. (1979)

The material used in this study was obtained from the brown clay in the oxidized zone of the silty clay, from approximately 3.0 to 3.6 m below grade (Man, 1998). Since the soil for the study was obtained from the oxidized clays, the physical properties of this unit will be discussed in further detail.

2.2 PROPERTIES OF WINNIPEG BROWN CLAY

The Winnipeg upper brown clay soil is characterized as a glacio-lacustrine. highly plastic swelling clay which may contain inclusions of gypsum, pebbles, and silt pockets (Baracos et al., 1979; Baracos and Graham, 1980).

The clay is firm to stiff and has a laminated structure of 2mm couplets of alternating clay and silt rich layers. At the top of the oxidized clay zone the soil is nuggetty and weathered with fissures; the fissures generally close with depth (Baracos et al., 1979; Baracos and Graham. 1980). Some properties of the Winnipeg brown clay are summarized in Table 2.1.

Table 2.1: Properties of Winnipeg Upper Brown Clay Soil

Property	
clay size % (<0.002mm)	70-85
moist unit weight	16.2-18.2 kN/m^3
dry unit weight	10.2-13.3 kN/m^3
liquid limit	65-110%
plastic limit	20-35%
plasticity index	40-75%
organic carbon	0.0028 (Man 1998)

Notes: Taken from Baracos et al. (1979) unless otherwise noted

The clay consists of approximately 75% montmorillonite, 10% illite 10% kaolinite and 5% quartz (Loh and Holt, 1974; Baracos, 1977; Baracos et al., 1979; Baracos and Graham, 1980). The silt fraction of the soil is mainly limestone and dolomite silts.

2.3 MINERALOGY OF WINNIPEG BROWN CLAY

Clay minerals are phyllosilicates, with laminar alumina alternating with laminar silica as shown in Figure 2.2.

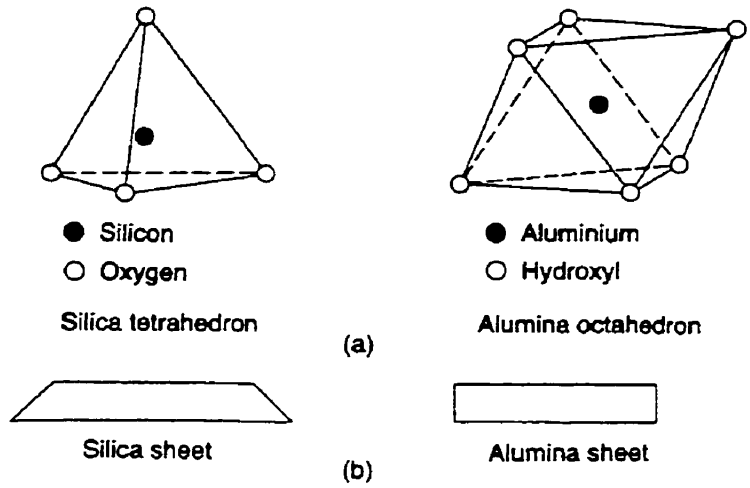

Figure 2.2: Silica and Alumina Units and Laminar Structures taken from Craig (1992)

Each layer is composed of linked tetrahedrons (either alumina or silica tetrahedrons). The difference between clay minerals results from different arrangements of the sheets in the mineral structure, as well as differing bonding mechanisms between adjoining sheets of tetrahedra.

Kaolinite is a 1:1 (silica layer:alumina layer) layer silicate structure that has alternating silica and alumina sheets held together by hydrogen bonding. Illite is a 2:1 layer silicate that consists of an alumina sheet between two silica sheets; the sheets are held together by weak bonding of non-exchangeable ions (potassium) and adjacent layers. Montmorillonite is also a 2:1 layer silicate but has a different type of bonding than illite.

The bonding between sheets in montmorillonite clays comes from water bonds and exchangeable cations. The ability of montmorillonite to adsorb more water molecules causes the high swelling capacity of the mineral (Craig, 1992; Klein and Hurlbut, 1993). The laminar and bonding arrangements for kaolinite, illite and montmorillonite are shown in Figure 2.3.

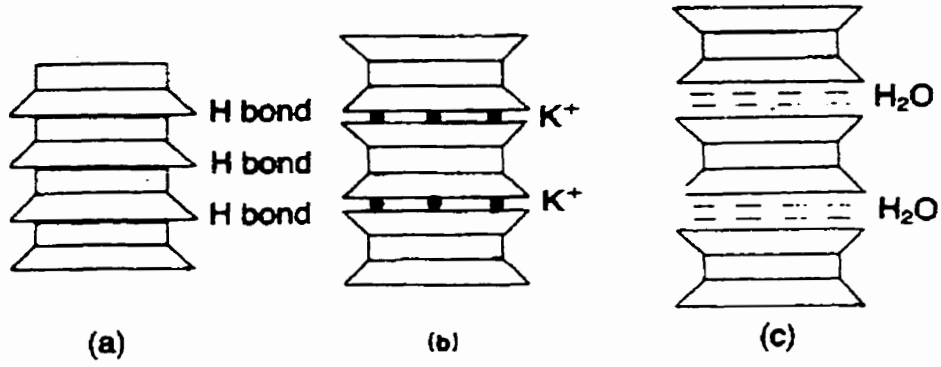

Figure 2.3: Mineralogical Structure of a) Kaolinite; b) Illite; c) Montmorillonite; taken from Craig (1992)

Clays generally carry a negative charge. The negative surface charge comes from substitution of magnesium and iron for aluminum and of aluminum for silicon.

The polarity of water molecules binds them to the negatively charged clay surface. This causes a layer of water to be adsorbed to the clay surface. The strength of the bonding between the water and the clay depends on the magnitude of the charge on the clay. The bonding decreases with distance from the clay surface until the bonding becomes governed by gravitational forces (Craig, 1992).

3.0 DIESEL FUEL CHARACTERISTICS AND PROPERTIES

3.1 CHEMICAL COMPOSITION OF DIESEL FUEL NO. 2

Diesel fuel #2 is a complex mixture of organic compounds. These organic compounds are classified as middle distillates, or more specifically, as the middle distillates of crude oil with hydrocarbons mostly in the range of C_9 to C_{20} with a boiling point from 160 to 360 °C (Millner et al., 1992). Diesel fuel #2 is composed of mostly alkanes (65 to 85% by volume) with aromatic and mixed aromatic compounds comprising the majority of the rest of the fuel (Block et al., 1991). Diesel fuel #2 is more easily termed a mixture of *n*-alkanes, monoaromatics, and polycyclic aromatic hydrocarbons (Atlas and Bartha, 1997; McGill et al., 1981).

3.2 PHYSICAL CHARACTERISTICS OF DIESEL FUEL

The general physical characteristics of diesel fuel are presented in Table 3.1. These specifications are based on the laboratory analyses of physical properties that allow for identification of different petroleum products. The properties of interest, namely solubility, hydrophobicity, specific gravity, vapour pressure, and viscosity are discussed in more detail in the following sections.

Table 3.1: Specifications and Normal Characteristics of Diesel Fuel No.2, after Block et al. (1991)

Property	Specification	Normal Values
API Gravity	30-39	31.8-34.0
Specific Gravity	0.830-0.876	0.85-0.87
Flash Point (°F)	135 (min)	145-165
Viscosity (mm^2/s @ 100 °F)	1.9-4.1	3.5-3.8
Sulfur (weight %)	0.50 (max)*	0.42-0.48
Colour, Saybolt	2.0 (max)	1.0-1.5
Corrosion, Copper Strip	#1 (max)	#1
Distillation, ASTM D86 (°F)		
Initial Boiling Point	-	300-320
10% Point	-	355-380
50% Point	-	450-550
90% Point	-	620-635
Final Boiling Point	-	665-675
Cetane Number (unitless)	42 (minimum)	45-46

*reduced to 0.10 after 1993

3.2.1 SOLUBILITY

Solubility is defined as the extent to which a compound will dissolve into an available water phase at equilibrium with pure product. The solubility of a compound is important since it aids in determining the partitioning of the contaminant between the sorbed and liquid phase as well as indicating whether contaminant will exist in the non-aqueous phase (NAPL phase) or in the dissolved (soluble) phase in soil water. It also

provides a measure of the degradability of the compound, since the contaminant must be present in the liquid phase for biodegradation of the contaminant to occur.

The many compounds that comprise diesel fuel each have their own distinct solubilities. Many of the compounds (i.e. aromatics and alkanes) are nonpolar to moderately polar compounds. These constituents will have limited solubility in water; generally, as the carbon number of the compound increases, the solubility will decrease. Polycyclic aromatid hydrocarbon (PAH) compounds have low solubilities except for the smaller PAH compounds such as naphthalene (Henner et al., 1997). The solubilities of some organic compounds are shown in Table 3.2.

Table 3.2: Solubility of Some Organic Compounds, adapted from Alexander (1999)

Compound	Solubility (mg/L)
hexadecane	0.000020
anthracene	0.05
decane	0.052
octane	0.66
phenanthrene	1.1
heptane ($C\text{-}H_{15}$)	2.9
biphenyl	7.2
naphthalene	31.0

For the group of compounds referred to as BTEX (benzene, toluene, ethylbenzene and xylenes), solubility is significant compared to other hydrocarbons. The BTEX compounds are toxic and potential carcinogens, so their presence in the subsurface (soil or groundwater) is important for environmental and health reasons.

3.2.2 HYDROPHOBICITY

The highly hydrophobic nature of most petroleum hydrocarbon compounds means that their methods of transport through soil media and biological media are far from understood today (Henner et al., 1997). A common problem with diesel contaminated soil is residual saturation of the diesel fuel. Since the organic compounds that comprise diesel fuel are generally insoluble, these compounds will preferentially remain in the soil as residual saturation rather than partition into the dissolved phase, where it would be more readily degraded. This problem is compounded in clay soils, where the inherent charge of the clay soil will also aid in retaining the compounds of the diesel mixture within the soil matrix.

3.2.3 SPECIFIC GRAVITY

The specific gravity of diesel fuel is normally between 0.85 to 0.87 at 4 °C, with a specified range of 0.830 to 0.876 (Block et al., 1991). Specific gravity is used to classify insoluble (NAPL) compounds such as diesel fuel into light non-aqueous phase liquids (LNAPLs) which have a specific gravity smaller than that of water, or dense non-aqueous phase liquids (DNAPLs) which are heavier than water. Since diesel fuel has a lower specific gravity than water, it is classified as an LNAPL compound.

3.2.4 VAPOUR PRESSURE

The vapour pressure of a compound is defined as the pressure that exists when a liquid reaches equilibrium with its surrounding atmosphere causing the number of

molecules leaving the liquid to be equal to the number of molecules entering the liquid (Munson et al., 1994; Dragun et al., 1991a). This means that the contaminant concentration in the liquid phase has stabilized with the atmosphere and the pressure of the contaminant in the vapour form is the vapour pressure of the contaminant. This is shown in Equation 3.1, which is the Henry's Law Equation:

$$K_H = \frac{C_g}{C_{sl}} \qquad [3.1]$$

where K_H is the dimensionless Henry's Law Constant, C_g is the concentration of the compound in the vapour phase, and C_{sl} is the saturation concentration of the compound in the liquid phase. Compounds with lower K_H values are less volatile than compounds with higher K_H values.

In general, PAH compounds have low volatilities (Henner et al., 1997). Diesel fuel is considered low to semi-volatile. This means the compounds in diesel fuel have low vapour pressures and will preferentially remain in the liquid phase. Again, the BTEX components are an exception. They are considered to be volatile organic compounds (VOCs).

The temperature profile of the compost heap will have an effect on the volatility of the substances within the compost. Generally, higher temperatures increase the vapour pressure of the compounds (Henner et al., 1997).

3.2.5 VISCOSITY

The viscosity of diesel fuel is of interest since it has an affect on how the fuel migrates through soil (Riser-Roberts, 1992). As the viscosity of a compound increases, its tendency to remain in the soil as residual saturation also increases. The viscosity effects are taken into account within the Darcy proportionality constant (K). This constant is inversely proportional to the viscosity of the fluid travelling through the soil (Domenico and Schwartz, 1990). Generally, diesel fuel has a viscosity of 3.5 to 3.8 mm^2 s^{-1} (Riser-Roberts, 1992).

3.2.6 HEALTH CONCERNS

Diesel contamination is a health concern and is covered under the CCME guidelines for pollutants. The BTEX constituents, discussed earlier, are potential carcinogens. Although no studies have been reported where diesel fuel was present as a lone contaminant, there is limited evidence that working in petroleum refineries poses a carcinogenic risk (IARC, quoted in Millner et al., 1992), particularly for skin cancers and leukemia. Studies on the genotoxic effects of diesel fuel and animal bioassays for carcinogenic potential of petroleum hydrocarbons have shown that potential exists for petroleum hydrocarbons to be mutagenic and carcinogenic (Millner et al., 1992).

3.2.7 PARTITIONING AND AVAILABILITY

For biodegradation to take place, the compound must first be present in the aqueous phase; if it is not present in the aqueous phase, it must partition into the aqueous

phase in order for biodegradation to initiate (DOD, 1994). The partitioning of the diesel fuel into the aqueous phase is governed by the sorption of the fuel to the soil, dissolution from the NAPL phase, or volatilization. The extremely high surface area of clay soils, which are fine-grained, provides clay soil with a high degree of sorptive capacity. The sorption of the diesel to the clay soil is also affected by the hydrophobicity of the diesel fuel, which increases the likelihood of sorption. The degradation of the compound can occur after a mass transport process acts on the sorbed diesel fuel, and the rate of biodegradation is limited by many factors, including the electron acceptors present in the soils. It should be noted that the possibility exists for the diesel fuel to become bound into the organic amendments of the co-compost mixture.

3.3 METABOLISM OF DIESEL FUEL

Diesel fuel can be utilized by heterotrophic microorganisms as both an energy source and a carbon source. Microorganisms release energy during metabolism of the diesel fuel through redox reactions. During aerobic reactions, the reaction process removes an electron from the hydrocarbon products and transfers it to oxygen, as an electron acceptor. In this way, the hydrocarbon compound is converted into new cellular material, water, and carbon dioxide. In general, the reaction proceeds as follows:

$$\text{hydrocarbon} + O_2 \rightarrow \text{energy} + \text{cells} + H_2O + CO_2 \qquad [3.2]$$

Oxygen is used as the electron acceptor, because the dominant electron acceptor process is dictated by the availability of the acceptors as well as the thermodynamically

favoured process. The reaction which produces the most energy is favoured over reactions that produce less energy. Once oxygen becomes unavailable, other acceptors may be used, such as nitrate (NO_3^-), carbon dioxide (CO_2) and iron (Fe^{3-}). The ranking sequence expected for reactions is aerobic degradation (O_2), denitrification (NO_3^-), manganese reduction (Mn^{4-}), iron reduction (Fe^{3-}), sulphate reduction (SO_4^{2-}) and the final stage, methanogenesis (CO_2). The reactions will proceed using the highest ranking available electron acceptor until it is depleted and then the microorganisms will be forced to utilize the next available electron acceptor. When the degradation substrate is a petroleum product, oxygen is the preferred electron acceptor for higher biodegradation rates (Dupont et al., 1991).

The aerobic hydrocarbon redox reactions require activation energy to proceed. The energy is provided by the enzymes produced by the microorganisms. A substrate compound requires a certain enzyme in order to produce a complex of enzyme-compound which results in an alignment necessary for the reaction to proceed (Dragun et al., 1991a). This enzyme may or may not be located within the microorganism's cell membrane (Dragun, 1998). The extracellular enzymes are used to help break down compounds that are too large to pass through the cell membrane (Man, 1998).

3.4 BIODEGRADATION OF DIESEL FUEL COMPONENTS

Microorganisms can degrade all petroleum hydrocarbons present in a diesel fuel mixture (Nyer, 1993), but at generally slow rates (Atlas and Bartha, 1997). Bacteria are mainly responsible for the degradation of petroleum hydrocarbons; however,

actinomycetes, molds and some algae may also degrade the hydrocarbons (Dragun et al., 1991a). Microorganism growth is often limited by the organic matter present within a system (Atlas and Bartha, 1997; Alexander, 1999). Generally, hydrocarbons are degraded by aerobic microbes (NCHRP, 1996).

Petroleum products are composed of many different organic compounds which will degrade at differing rates (Alexander, 1999; NCHRP, 1996). The same compound will be degraded at different rates when present in different NAPLs (Alexander, 1999). In general, the *n*-alkanes are degraded the fastest, followed by branched alkanes, aromatics, and cyclic alkanes (Douglas et al., 1992; Cho et al., 1997a; Atlas and Bartha, 1997). Generally, as the chain length or branching increases, the compounds become more resistant to degradation. Compounds with short chain lengths (C_9 or less) can be toxic to microorganisms and are also difficult to degrade (Atlas and Bartha, 1997), as are the aromatic compounds (Cho et al., 1997a).

The rate of biodegradation depends on the range of conditions required by the microorganisms that are performing the degradation. Factors that may affect the rate of utilization include moisture content, pH, nutrient supply and temperature. The pH of the environment affects the cellular functions and cell membrane transport of the substrate. Generally, most bacterial species grow best in a pH range of 6 to 8 (Dragun, 1988). The moisture content should be between 50 to 70% for petroleum hydrocarbon remediation processes to occur, because above 70% moisture, anaerobic conditions may occur, and below 50% moisture, transport of substrate may be inhibited (Cookson, 1995).

In general, compounds that have higher solubilities are more mobile and more

bioavailable, and thus more biodegradable (Riser-Roberts, 1992) because the liquid phase is where microbial metabolism occurs. However, it should be noted that the high solubility does not indicate high levels of biodegradation; for some compounds, the high solubility may indicate that the compound is present in enough strength to be toxic to the microorganisms.

Another factor in biodegradability is the "age" of the contaminant. Aged soils (soils with a longer contaminant-chemical contact time) may contain only recalcitrant compounds which are resistant to biodegradation (Berg et al., 1998). Berg et al. (1998) examined a soil which proved to have adequate hydrocarbon degrading microorganisms (shown through plate counts) even though biodegradation was minimal. A "younger" (and different) soil was shown to have a 39% reduction in TPH levels.

3.4.1 AEROBIC BIODEGRADATION OF *n*-ALKANES

Alkanes are also termed saturated hydrocarbons, since alkanes are carbon-chain compounds that exhibit single bonding for carbon-carbon bonds and carbon-hydrogen bonds, and may also be called aliphatic hydrocarbons (McMurry, 1992). Straight-chain alkanes are called normal alkanes, or *n*-alkanes. Alkanes are affected first by monooxygenases and dioxygenases which use oxygen as the terminal electron acceptor for degradation processes (Atlas and Bartha, 1997). Monooxygenase uses one atom of oxygen to create a primary alcohol through oxidation of the terminal methyl group, as shown in Equation 3.3 (Atlas and Bartha, 1997).

$$R - CH_2 - CH_3 + O_2 + NADPH_2 \rightarrow R - CH_2 - CH_2 - OH + NADP + H_2O \quad [3.3]$$

Dioxygenase uses two atoms of oxygen to create a hydroperoxide which is then reduced to an alcohol and water (Equations 3.4 and 3.5).

$$R\text{-}CH_2\text{-}CH_3 + O_2 \rightarrow R - CH_2 - CH_2 - OOH \quad [3.4]$$

$$R\text{-}CH_2\text{-}COOH + NADPH_2 \rightarrow \quad R\text{-}CH_2\text{-}CH_2\text{-}OH + NADP + H_2O \quad [3.5]$$

Once either monooxygenase or dioxygenase has acted to create an alcohol, the alcohol is then further transformed into a fatty acid and aldehyde. From this point, the β-oxidation process acts upon the compound (Atlas and Bartha, 1997; McGill et al., 1981), shown in Equations 3.6 to 3.10. β-oxidation acts upon the fatty acid formed by converting the fatty acid into a coenzyme form. The acetyl CoA group is cleaved and the fatty acid loses two carbon groups, whereupon the sequence repeats. The CoA groups are converted to carbon dioxide through the tricarboxylic acid cycle (Atlas and Bartha, 1997; Burton, 1997).

$$R\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}COOH \xrightarrow{+CoA} R\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}COCoA \quad [3.6]$$

$$R\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}COCoA \xrightarrow{-2H^+} R\text{-}CH_2\text{-}CH=CH\text{-}COCoA \quad [3.7]$$

$$R\text{-}CH_2\text{-}CH=CH\text{-}COCoA \xrightarrow{+H_2O} R\text{-}CH_2\text{-}CHOH\text{-}CH_2\text{-}COCoA \quad [3.8]$$

$$R\text{-}CH_2\text{-}CHOH\text{-}CH_2\text{-}COCoA \xrightarrow{-2H^+} R\text{-}CH_2\text{-}CO\text{-}CH_2\text{-}COCoA \quad [3.9]$$

$$R\text{-}CH_2\text{-}CO\text{-}CH_2\text{-}COCoA \xrightarrow{+CoA} R\text{-}CH_2\text{-}CO\text{-}CoA + CH_3\text{-}CO\text{-}CoA \quad [3.10]$$

The products resulting from β-oxidation are carbon dioxide and water. It should be noted that the β-oxidation process does not require oxygen to proceed and can proceed anaerobically (Atlas and Bartha, 1997).

3.4.2 Aerobic Biodegradation of Monoaromatic Compounds

Monoaromatic compounds are compounds that contain one benzene ring, such as benzene and toluene, and are degraded through the process of creating a cis-dihydrodiol which is then further oxidized to a catechol (McGill et al., 1981). Procaryotic cells tend to use dioxygenase to form the cis-dihydrodiol while eucaryotic cells tend to use monooxygenase which forms an arene oxide which is then transformed to trans-dihydrodiol and then further to a catechol (McGill et al., 1981).

Once the catechol has been formed, ring cleavage processes can occur. Ring cleavage occurs through either ortho cleavage or meta cleavage (Ribbons and Eaton, 1982).

3.4.3 Polycyclic Aromatic Biodegradation

Biodegradation of polycyclic aromatic hydrocarbons is generally quite complex due to the fused ring structure of these compounds. Oxygenation occurs through enzymes forming a dihydrodiol. This compound can be further oxidized and then through salicylic acid is transformed to a catechol. From this point, degradation occurs as for monoaromatics. The TCA cycle reduces the compound to CO_2 and H_2O.

4.0 REMEDIATION TECHNOLOGY

Several remediation options exist that have proven effective for decontamination of hydrocarbon contaminated soils. Remediation methods can be separated into two basic types, *in situ* and *ex situ* technologies. Several methods of both types have been proven effective for hydrocarbon-contaminated soils. These methods and their applicability to the heavy clay soils present in Manitoba will be discussed in the following sections.

4.1 IN SITU TREATMENT TECHNOLOGIES

In situ treatments consist of biodegradation, bioventing, soil flushing, soil vapour extraction (in situ), thermally enhanced soil vapour extraction and natural attenuation, all of which have been proven average to better as a fuel degradation technology (DOD, 1994).

Biodegradation, as a treatment technology, is defined as the process of adding water-based solutions to contaminated soils in situ (DOD, 1994). These solutions contain nutrients or oxygen to enhance biological degradation. The solutions may also be created using additives to help desorb contaminants from the soil matrix, which will also aid in biological degradation of contaminants. This technology is used in conditions where oxygen is sufficient to allow aerobic microbial degradation to convert organic contaminants into carbon dioxide and water. In systems where oxygen is not present in sufficient amounts to sustain aerobic degradation, anaerobic degradation will convert the organic contaminants to methane, small amounts of carbon dioxide and trace amounts of hydrogen gas. Biodegradation is generally performed by injection of groundwater or

uncontaminated water that has been mixed with the chosen additives. Occasionally microorganisms (either naturally occurring or engineered) that have an affinity for the contaminant to be degraded will be introduced to the site; this is termed bioaugmentation (Cookson, 1995; DOD, 1994). Biodegradation and bioaugmentation have been proven effective on petroleum-hydrocarbon contaminated soils (Alexander, 1999; DOD, 1994), but the processes may prove difficult in clay soils. This is due to the low permeability of the clay which prevents microorganisms from moving easily through the soil to the contamination for degradation purposes, and will preclude the movement of the additive solutions through the soil (Alexander, 1999).

Bioventing is the process of stimulating naturally occurring biodegradation in soils by adding oxygen to sustain the degradation process using low air flow rates (Burton, 1997; DOD, 1994). The oxygen is generally supplied through direct injection of air into the soil. The addition of oxygen will help maintain microbial degradation and will aid in the removal and degradation of volatile substances, which will travel slowly through zones of microbial activity. It has proven effective on petroleum hydrocarbon contaminated soils (DOD, 1994), but it has been noted that the process is less effective to ineffective on very moist soils or soils with fine grain sizes. This process is limited by the permeability of the soil (NCHRP, 1996; Alexander, 1999). Low permeability soils such as Lake Agassiz clay may show little response to bioventing processes.

Soil flushing is the process of using water, or water mixed with a detergent to clean the soil. The water is applied directly to soil or injected into groundwater. The contaminant migrates into the groundwater through the process of leaching, and the

groundwater is collected and treated separately (DOD, 1994). This process is simply an extraction process; the collected groundwater may need to be treated prior to release. The permeability of soils is again a limiting factor, and the low permeability of clay will severely limit the flushing rate (NCHRP, 1996).

Soil vapour extraction (SVE) is used to remove contaminants from the unsaturated zone of soils. This method involves the application of a vacuum to the soil in order to extract air from the soil, removing volatile contaminants (DOD, 1994). The air can then be treated, combusted, or vented to the atmosphere. The method is generally acceptable for compounds with a Henry's Law constant of 0.01 (unitless) or a vapour pressure greater than 0.5 mm Hg (DOD, 1994). This treatment method is also limited by the air permeability of the contaminated soil and the moisture content of the soil. The low permeability and high moisture content of Manitoba clay soils may render this technology unsuitable for clay soils (NCHRP, 1996). Thermally enhanced soil vapour extraction is the process of using steam or hot air in the process of soil vapour extraction (see above), but has the same permeability limitations as SVE.

Natural attenuation has been attempted on some soils. It is the option of leaving the remediation processes to nature, allowing the natural microorganisms and environmental conditions to dictate the degradation of the soil (DOD, 1994). It involves site monitoring to ensure that the natural attenuation is meeting the required guidelines for contaminant concentration before potential exposure pathways are attained.

The in situ treatment methods are compared and summarized in Table 4.1.

Table 4.1: In-situ Treatments for Fuel Contaminated Soils, adapted from DOD (1994)

Treatment Method	Current Usage	Applicability	Function	Cost (overall)
Biodegradation	Wide	Better	Destruction	Average
Bioventing	Wide	Better	Destruction	Better
Soil flushing	Limited	Average	Extraction	-
Soil vapour extraction	Wide	Better	Extraction	Better
Thermally enhanced SVE	Limited	Better	Extraction	Average
Natural attenuation	Limited	Better	Destruction	Better

It should be noted that the applicability column does not apply to only clay soils, but to all soil types. The in situ treatments that have been used for hydrocarbon remediation are all (with the exception of natural attenuation) limited by the soil permeability which renders them of little use when treating a heavy clay soil such as the Lake Agassiz clay soil in Manitoba.

4.2 EX SITU TREATMENT TECHNOLOGIES

The ex situ methods are generally more useful for treatment of clay soils. According to the DOD (1994), controlled solid phase biological treatment, slurry phase biological treatment, soil washing, soil vapour extraction, solvent extraction (chemical extraction), high temperature thermal desorption, low temperature thermal desorption, landfarming and composting have all been proven adequate as fuel degradation technologies.

Controlled solid phase biological treatment processes use excavated soils mixed with soil amendments to enhance degradation. The mixture is placed in an aboveground enclosure in treatment cells and biopiles (DOD, 1994). Biopiles consist of soil which has been excavated, combined with nutrients and structural modifiers (if necessary), and placed in a distinct treatment area, and may include a leachate collection system and an aeration system. The area of treatment (the treatment cell) may be closed to prevent rainfall or other moisture from entering the biopile. The primary limitation of this process is the length of time necessary to treat material, especially with clay soils, where the strongly sorbed hydrocarbons will be remediated very slowly.

Slurry phase biological treatment is the creation of an aqueous solution of contaminated soil, water, and additives. The slurry is mixed in order to allow the microorganisms to maintain sufficient contact with soil, and to keep the soil suspended in solution (DOD, 1994). The typical solids content is 10 to 40% by weight, and oxygen is added to the slurry to optimize biodegradation processes. Acids or alkalis may be added to control the pH of the slurry if desired (DOD, 1994). This technique has been used successfully on soils contaminated with petroleum hydrocarbons and petrochemicals (DOD, 1994). Some of the problems associated with this method are that non-homogeneous soils can create serious handling problems, and the process creates a wastewater that must be dealt with. The fines present in soils such as clays cause an expensive removal problem during dewatering (NCHRP, 1996).

Soil washing is the process of washing the soil with water, which may be augmented with a leaching agent, surfactant or chelating agent to help remove organics

from the soil particles (DOD, 1994). Soil washing follows one of two methods: suspension of the soil in the wash solution, or separation of the soil by particle size separation or gravity separation, and dealing with these smaller volumes of soil. The reason for separation is to reduce the volume of contamination (contaminants generally bind to silt and clay, not gravels and sands). This process is used for fuels and SVOC's. Fine soil particles may need a polymer addition to the solution in order for them to be removed from the fluid. Also, the washing fluid will require treatment after the soil is removed from solution (DOD, 1994).

Ex situ soil vapour extraction (SVE) uses a vacuum applied to the soil to volatilize and collect organics from the soil (DOD, 1994). Soil is excavated and placed over a network of piping that applies a vacuum to the soil. This method is used for VOC's. Some disadvantages to the method are that air emissions may require treatment and the process has a large areal requirement. This process is limited by the permeability of the excavated soils and will not perform well on clay soils.

Solvent extraction (chemical extraction) uses a chemical solvent to remove the organic contaminant from the soil. The soil is placed with the solvent in an extractor and mixed. The solvent and contaminant is then removed by separation (DOD, 1994). This method is simply a separation method. It has been shown effective on VOCs and petroleum wastes (DOD, 1994), but has low effectiveness in clay soils.

High temperature thermal desorption (HTTD) is the process of heating soil to 320 to 560 ^{0}C (600 to 1000 ^{0}F). This volatilizes the contaminants and water in the soil. The gas produced is collected and treated separately (DOD, 1994). The method has been

proven effective on SVOCs and PAHs. It has also been used (at a less cost-effective level) for the treatment of fuels and VOCs. However, the method was attempted at the Domtar Site in Winnipeg, but proved to be ineffective in reducing the contaminant to acceptable levels due to the high amount of clay in the soil (Burton, 1997). According to the DOD (1994), clay and silty soils can affect reaction time (lengthening the time to degrade) due to the strong binding of contaminants to the soil. Low temperature thermal desorption (LTTD) is the same process as HTTD except that the temperature range for the process is lowered to 90 to 320^{0}C (200 to 600^{0}F). As with the high temperature process, the gases must be collected and treated separately (DOD, 1994).

Landfarming is the process of spreading contaminated soil on an uncontaminated soil surface and then periodically tilling the soil to aerate the contaminated soils (Burton, 1997; DOD, 1994; Alexander, 1999; Cookson, 1995; Henner et al., 1997). Nutrients, such as nitrogen and phosphorus, may also be added to the soils to stimulate bioactivity while landfarming. Often the moisture content becomes a limiting factor, requiring soil to be periodically watered to maintain sufficient moisture levels for biodegradation (Alexander, 1999). This process has the advantage of being performed on-site, and generally does not require a leachate collection system. Another advantage to landfarming is the low cost of equipment and maintenance of the process (Alexander, 1999). The limitations of this process include the amount of space necessary to landfarm contaminated soils, the lack of control over biological processes, and the slow rate of degradation. It is often used to degrade the recalcitrant compounds such as heavier hydrocarbons from soil.

Co-composting is the practice of combining contaminated soil with compost, as bulking agents and organic amendments (Alexander, 1999; DOD, 1994; Cookson, 1995; Henner et al., 1997). This technology has been shown to be effective at degradation soil contaminated with explosives (Williams and Keehan, 1993; Ziegenfuss et al., 1991), chlorophenol (Alexander, 1999; Valo and Salkinoja-Salonen, 1986; Laine and Jorgensen, 1997) and hydrocarbons (Al-Daher et al., 1998; Beaudin et al., 1996; Hupe et al., 1996; Joyce et al., 1998). It has been suggested that composting of petroleum products may be performed with high contaminant concentrations (Henner et al., 1997). Co-composting may prove to be a viable alternative to landfarming/excavation processes or in situ biological processes. Sites having clay soil with volatiles already weathered through dissolution, leaching, volatilization or biodegradation will possess a residual product that is very recalcitrant. This recalcitrant contaminant may require more aggressive treatments than biopiling or landfarming.

The ex situ methods are compared and summarized in Table 4.2. The applicability of each method is for all soil types, not specifically clay.

Table 4.2: Ex-situ Treatment Methods Comparison adapted from DOD (1994)

Treatment Method	Current Usage	Applicability	Function	Cost (overall)
Controlled Solid Phase Bio. Treatment	Wide	Better	Destruction	Better
Slurry Phase Bio. Treatment	Limited	Better	Destruction	Average
Chemical Reduction/Oxidation	Limited	Below average	Destruction	Average
Soil washing	Limited	Better	Extraction	Average
Soil vapour extraction (ex-situ)	Limited	Average	Extraction	Better
Solvent Extraction	Limited	Average	Extraction	Worse
High Temp. Thermal Desorption	Limited	Average	Extraction	Average
Low-Temp. Thermal Desorption	Wide	Better	Extraction	Better
Landfarming	Wide	Better	Destruction	Better
Composting	Wide	Better	Destruction	Better

Most co-composting projects have involved soils such as sands, silty sands, and gravels with little or no clay content, so that the effects of working with heavy clay soil have not yet been investigated. The first step to using co-composting on a particular soil type is to characterize the soil and contaminants present.

5.0 COMPOSTING LITERATURE REVIEW

5.1 COMPOSTING – GENERAL PROCESS AND INFORMATION

Compost is a mixture of organic materials which, when combined, undergoes rapid degradation, stabilizes the materials, reduces volume and creates useful end products. The degradation which takes place may be either aerobic (requiring oxygen) or anaerobic (requiring a lack of oxygen) degradation processes.

The composting process is dependent on a variety of factors. The oxygen transfer, carbon:nitrogen ratio (C:N), moisture content, structure of the compost mixture, temperature, and length of time composting occurs (material retention time). Another factor which affects compost performance is the compression which occurs in the compost pile, which has an affect on both the structure of the compost pile as the pile settles and on the oxygen transfer rates. The compost "recipe" (ratio of materials in mixture) can be optimized to create a mixture that will compost quickly and effectively.

Pore space oxygen levels should be no less than 5% to ensure that oxygen is not a limiting factor in the composting process (NRAES, 1992). The structure of the compost pile is important as it influences the settling and compression which occurs in the compost pile. Particle size should be generally from 0.3 cm to 1.3 cm diameter, but the range will depend on the materials used in the compost pile.

Chen (1998) examined the effect of compaction on compost performance. Woodchip-biosolids compost that experienced a compressive loading of 12 kg over an area of 0.00916 m^2 (12.9 kPa) showed a reduction of 43% in free air space (FAS)

measurements. Straw-biosolids mixtures showed a 74% reduction in FAS and the leaves-biosolids mixture showed a reduction of 85% in the FAS. Although the woodchips-biosolids mixture did not show the highest initial FAS, it is clear that the woodchips:biosolids mixture maintains the highest FAS measurements (21%, as opposed to 12% and 5% for the straw and leaves mixtures respectively) when under compressive loading. The effects of three different loading levels on the FAS of the three mixtures used in Chen (1998) are shown in Table 5.1.

Table 5.1: FAS under compression, adapted from Chen (1998)

Feedstock	FAS original (%)	FAS after 4.28 kPa (%)	FAS after 8.57 kPa (%)	FAS after 12.85 kPa (%)
biosolids/woodchips	37	26	24	21
biosolids/straw	47	23	15	12
biosolids/leaves	34	10	8	5

The carbon:nitrogen ratio is important because carbon is necessary for microorganism growth and energy, while nitrogen is necessary for microbial protein synthesis and reproduction. Ideally, the carbon:nitrogen ratio should be 20:1 to 40:1, and preferably in the range of 25:1 to 30:1. The moisture content of the compost mixture is important, as the water provides a transport mechanism for microorganisms and nutrients and is a medium for chemical reactions to take place. Ideal moisture content ranges from 40 to 65%, with the preferred range from 50 to 60% (NRAES, 1992). Experimental work has shown that moisture content in the piles affects respiration rate of microorganisms (Al-Daher et al., 1998).

The temperature of a composting process occurs in two ranges, mesophilic at 10 to 41 °C (50 to 105 °F) and thermophilic at over 41 °C (105 °F). Mesophilic temperatures allow for composting, but the recommended temperature range is within the thermophilic range at 43 to 66 °C (110 to 150 °F). The thermophilic, or active range (Joyce et al., 1998; Tchobanoglous et al., 1993; Haug, 1990) destroys pathogens above 55°C (131 °F) and weed seeds above 63°C (145 °F). Above 60 °C (140 °F) the microbes begin to be affected by the heat, and composting slows. Above 71 °C (160 °F) many microorganisms die or become dormant, necessitating temperature monitoring of compost. The microorganisms most active in compost are actinomycetes, fungi, and bacteria (Tchobanoglous et al., 1991; Haug, 1993), which occur in both mesophilic and thermophilic species within compost. The bacteria are generally most abundant, with a wide variety and are present at the beginning of the compost process. The fungi are more tolerant of low moisture content and low pH but are less tolerant of low oxygen than the bacteria. The fungi are better decomposers of woody or decay resistant materials within the compost. Actinomycetes are aerobic filamentous bacteria which are tolerant of low moisture content conditions, but are sensitive to acidic conditions. The fungi and actinomycetes become more important as the compost process progresses. The fungi become more important, because when the readily available and easily degraded carbon sources are depleted, the fungi are capable of degrading the decay resistant materials. Actinomycetes also become important, since the moisture content of the compost decreases during the composting process (unless augmented by water addition). The microorganisms use oxygen as the electron acceptor (under aerobic conditions).

There are three basic types of compost technology; the in-vessel system, the static pile system, and the windrow system (Cookson, 1995; Tchobanoglous et al., 1993). The three composting operation systems are compared in Table 5.2, adapted from Cookson (1995).

Table 5.2: Composting Technology Comparison from Cookson (1995)

	Windrow System	**Static Pile System**	**In-vessel System**
operational skill	low	moderate	high
process flexibility	high	medium	low
material load flexibility	high	medium	medium
process control	low	medium	high
moisture control	low	medium	high
air emission control	low	medium	high
runoff control	medium	medium	high
space requirement	high	medium	low
pathogen destruction	medium	high	high
climatic dependency	high	medium	low
capital cost	low	medium	high
maintenance cost	low	medium	high

5.2 Composting Of Contaminated Soil

The compost mixture can be mixed with contaminated soils to aid in the degradation of the contaminants. This process is called co-composting, and it has been shown to be effective in reducing some organic contaminants. It has been used successfully to remediate TNT and other explosives-contaminated soils, chlorophenol-contaminated soils, as well as soils contaminated with hydrocarbon compounds such as an oily waste.

or mineral oil and grease.

5.2.1 TNT AND OTHER EXPLOSIVES COMPOSTING

Williams and Keehan (1993) reported degradation of explosives-contaminated soils using co-composting. The variables they examined included the amendment composition, control of environmental conditions, amount of soil added to compost, and the effects of bioaugmentation. However, the soil type contaminated with explosives was not discussed in the paper, other than the statement that it was excavated from a lagoon, and contained 13,380 mg kg^{-1} of tri-nitrotoluene (TNT), 1071 mg kg^{-1} of cyclotri-methylenetrinitramine (RDX), and 273 mg kg^{-1} of cyclotetramethylenetetranitramine (HMX). The uncontaminated soil used in the control reactor was also not discussed; it is unknown if the soil types were similar.

The first step in their experiment was to run two reactors with different amendment compositions and 10% contaminated soil by volume, to determine the amendment mixture to be used for further experimentation. The final amendment mixture chosen had a C:N ratio of 30:1, and consisted of sawdust, apple pomace, chicken manure and chopped potato waste. It was not described how this mixture was chosen, nor how it was determined as the optimum amendment mixture of the two mixtures used. The second amendment mixture tested was not discussed in the paper.

Williams and Keehan (1993) then examined static pile systems, running eight different static pile compositions. The control static pile consisted of 10% uncontaminated soil by volume. Five different amendment ratios were tested, at 7, 10,

20, 30, and 40% contaminated soil by volume. One static pile was bioaugmented, while the final static pile was run using 10% contaminated soil by volume and utilized a different amendment recipe along with 200g of ^{14}C-TNT spiked compost. The compost was monitored for pH, moisture content and water retaining capacity. The highest percentage removal of explosives occurred at 7% contaminated soil loading by volume. However, for TNT, at 30% contaminated soil the highest removal, 98%, occurred. The total reduction of the three explosives examined (TNT, RDX, HMX) indicated that the highest reduction occurred at the lowest soil:organic amendment ratio. The reduction levelled off at approximately 30%, and at 40% almost no reduction occurred in the HMX and RDX, and significantly less reduction occurred for the TNT contamination. The concentration of TNT in the soil for tests in the range of 7 to 30% contaminated soil reached approximately the same value after approximately 45 days of composting and remained at these levels. The 40% contaminated soil by volume remained significantly above this value for the duration of composting (90 days).

From this research, it was suggested that there were 7 areas for future research in order to overcome the serious dearth of information on the specific behaviour of compounds in a composting setting. The seven areas of further study suggested by Williams and Keehan (1993) are:

(1) definition of the ultimate fate of organics in compost
(2) examination of the potential of adverse impacts of toxic organics which may remain bound in compost
(3) amendment selection strategy definition
(4) definition of optimal operating conditions, development of compost systems meeting criteria
(5) definition and optimization microbial ecology of degradation systems

(6) improvement of the chemical analysis methods for compost testing
(7) definition of contaminant degradation rate limiting parameters

These seven areas will allow for a more complete understanding of the fate of contaminants during the co-composting process.

Ziegenfuss et al. (1991) state that the incomplete mineralization of organics may biologically convert to organic products and become part of the compost residue. They examined TNT-contaminated soils. Their past lab work had indicated that 66.5% of the ^{14}C activity became bound into the compost residue after 6 weeks of thermophilic activity and could not be extracted using conventional solvent extraction techniques. However, on combustion of the compost residue, it was released as $^{14}CO_2$. They observed a 37 to 46% total reduction in ^{14}C-RDX, not including results found during combustion as $^{14}CO_2$ as reduced ^{14}C-RDX. They then created 2 aerated static piles, one at 35 °C (mesophilic) and one at 55 °C (thermophilic), with both piles containing 24% by weight of explosives-contaminated soil. The piles were maintained for 153 days, during which both piles exhibited rapid moisture depletion and required rewatering. Thermophilic conditions caused better levels of remediation of the explosives contamination, and the significant variation in temperatures within the piles (generally lower at pile edges) affected the degradation rate at different points within the pile. The mesophilic and thermophilic piles reached the same remaining concentration of TNT after approximately 140 to 160 days, but the thermophilic pile degraded the TNT more rapidly than the mesophilic pile.

Bruns-Nagel et al. (1998) composted TNT-contaminated soil in reactors using an anaerobic/aerobic process. The organic amendments were a mixture of chopped sugar beets and straw, which were mixed with the TNT-contaminated soil. This mixture was placed into 4 L reactors. During the anaerobic phase of 19 days, tap water was percolated

through the reactor at a flow rate of 12 mL-h^{-1} and a pH of 7.0 ± 0.2. After anaerobic treatment, the compost was aerated through an outlet at the bottom of the compost reactor. During the anaerobic phase, almost 90% of the TNT was transformed. The aerobic phase led to an elimination of most of the remaining TNT along with the degradative products of the TNT.

5.2.2 Chlorophenol (and Other Phenol) Composting

Chlorophenols have also been remediated using composting methods. Valo and Salkinoja-Salonen (1986) used a sand and gravel soil which had been contaminated with chlorophenols. The windrow composting mixture was created from 70 m^3 of contaminated soil, 35 m^3 softwood bark, and 3 m^3 of ash. The extractable chlorophenol concentration in soil dropped from an average of 212 mg kg^{-1} of dry compost to 30 mg kg^{-1} of dry compost after four summer months of composting, and to 15 mg kg^{-1} of dry compost after 16 months, including a second summer of composting. The initial concentration of chlorophenols in soil was 400 to 500 mg kg^{-1} of soil. They determined that the first two months of composting were the most effective (although no samples were taken in this interval, only at the endpoints). This indicates that the most effective composting occurs sometime during the first two months of composting. The results also indicated that the forms of microbial inoculum used during the experiment did not have a significant effect on the performance of the degradation of the chlorophenols during the composting process. They were able to confirm degradation through the production of $^{14}CO_2$ from radiolabelled chlorophenols; however, this was performed in the laboratory using mature compost from the field scale trials, not at field scale. Binding of chlorophenols to the compost matrix was not determined. Benoit and Barriuso (1996)

contaminated wheat straw with 2-4, dichlorophenol and 4-chlorophenol and then composted some of the straw over a 6 month period. They combined this material (both uncomposted and composted straws) with loamy soil that had passed a 2 mm sieve. They discovered that the stabilization of the chlorophenols was enhanced by the bound-residue formation which occurred. The composted straw decreased the mineralization of chlorophenols (seen as $^{14}CO_2$ generation). The composted straw mixture had extractable chlorophenol concentrations a factor of 0.55 lower for 4-chlorophenol and 0.36 lower for 2-4, dichlorophenol.

Laine and Jorgensen (1997) used chlorophenol contaminated soil mixed with woodchips for biodegradation and observed that after about nine weeks the percentage removal of chlorophenol began to level off at near 98% for high initial concentrations of chlorophenols, and at near 80% for low contamination levels of chlorophenols. This time period correlated to an observed drop in temperature within the compost at about week nine. This also correlated to a drop in basic respiration and substrate induced respiration. They also observed that there was little benefit to adding remediated soil or mature compost to the mixture. The soil type used during the study is unknown.

Laine et al. (1997) composted chlorophenol contaminated soil in four different compost mixtures. The reference pile consisted of contaminated soil, bark chips and nutrients. The other three compost piles were constructed of similar material, but received small amounts of microbial inoculum in the form of straw compost (pile 2), remediated soil (pile 3), and remediated soil mixed with contaminated woodchips (pile 4). After 9 weeks of composting, the first three piles received an additional amount of heavily contaminated soil. The concentrations of chlorophenols in the piles after the additional heavily contaminated soil ranged from 680 to 1100 mg kg^{-1} dry compost. The

compost piles were allowed to compost for a further 16 weeks, after which time the extractable chlorophenol concentration in the piles ranged from 34 to 67 mg kg^{-1} in piles 1 to 3, and was 200 mg kg^{-1} in pile 4, which was initially (week 0) 1800 mg kg^{-1}. The results indicate that heavier contaminant loads increase the treatment time of the soil, as seen in pile 4. This is likely due to heavier contaminant loads being toxic to microorganisms, hindering the growth of the microbial community which degrades the chlorophenols. The results also indicate that the form of microbial inoculation used with low chlorophenol concentration (piles 2 and 3) showed little difference in the final concentrations of the chlorophenols, indicating that the inoculum was not a necessary part of degradation of the chlorophenol contamination. The soil type used during the study is unknown.

5.2.3 Hydrocarbon and Fuel Composting

Co-composting has been used effectively on calcareous sandy soil from Kuwait, reducing extractable levels of oil contamination by 54.5% for lightly contaminated soils (10.92 mg PAH kg^{-1} soil) and by 60% in heavily contaminated soils (15.2 mg PAH kg^{-1} soil) over a period of 8 months (Al-Daher et al., 1998). The compost mixture consisted of woodchips and either dried sewage sludge, mature compost, or both.

Cho et al. (1997b) examined the effect of differing soil amendment materials on oil-contaminated soil from Kuwait. The soil was a calcareous sandy soil (silt content of less than 6%). The amendments used were a commercial bark manure (Fujimi Bark Inc.). hyponex powder (1.7% NH_4-N, 5.6% NO_3-N, 8.0% PO_4), baked diatomite (0.9 to 1.5 mm diameter, primarily composed of silica dioxide), an oil degrading bacterial culture, microporous glass and charcoal from coconut husks. After 36 weeks of 30 °C

temperatures, the highest levels of degradation occurred with a bark/hyponex/diatomite mixture, with approximately 70% residual hydrocarbons. The results from the experiment from the samples collected 9 times over the 36 week run, indicated that the sampling results were affected by the sampling technique. This was shown in the variability of the results for residual hydrocarbons, which fluctuated greatly over the 36 week run. The inaccuracy was credited to the non-homogeneity of the mixture, which caused representative sampling problems.

Beaudin et al. (1996) co-composted weathered hydrocarbon contaminated soils. The study was performed to analyze the degradation of mineral oil and grease (MOG) during co-composting. The first soil type was contaminated at 17,000 $\mu g\ kg^{-1}$ MOG on average, and was a sandy soil (83.5% sand). The second soil type was uncontaminated and was also a sandy soil (97.1% sand). For their first experimental phase, their compost mixture contained mostly leaves and alfalfa pellets (Purina brand rabbit chow). They ran several reactors with the same composting mixture of soil, alfalfa, leaves, and mature compost. The data showed that the rates of carbon dioxide generation and oxygen generation were affected by the temperature changes (heat generation) within the reactors. The rates of generation of CO_2 and O_2 were low for the first 15 hours, then rose rapidly. The temperatures within the reactors remained constant for about 6 hours then rose quickly to 53 ^0C, at which point aeration was used to control the temperatures, which gradually fell to room temperature. The gas generation also decreased, to less than 10 $mmol\ hr^{-1}\ kg^{-1}$ initial dry compost by the twelfth day. The extractable MOG concentration was decreased from 17,800 $mg\ kg^{-1}$ of dry cocompost to 7500 $mg\ kg^{-1}$ of dry co-compost over 105 days.

They also ran a separate experiment with 2 reactors to allow for the determination

of MOG originating from the compost. The reactors were loaded using soil, alfalfa, leaves and nutrients, as well as a microbial inocolum. This experiment was conducted to determine the amounts of mineral oil and grease originating from the alfalfa and leaves used for the composting. They found that 50% of the MOG that had originated from soil had been degraded after 105 days. Over 287 days, the fraction of MOG that degraded from the soil increased to 73%.

Liu and Cole (1995) mixed mature yard waste compost with pesticide-contaminated soil to determine the amount of compost that was needed to significantly degrade the pesticides while encouraging plant growth on the compost and optimizing microbial activity. The contaminated soil consisted of 27% sand, 32% silt, 19% clay and 22% gravel, with a very low organic content. The compost used in the experiment was mature yard waste compost that had undergone thermophilic composting. They analyzed additions of 0, 1, 5, 10, 20, and 40% compost (wt/wt). They examined plant dry matter production (sweet corn, greenhouse grown, 4 weeks), and microbial activity as dehydrogenase and extractable pesticide content. They found that the maximum stimulation of microbial activity (as indicated by dehydrogenase) and extractable pesticide reduction occurred at 20% compost by weight. According to Liu and Cole (1995), the expectation would be that the optimal amount of compost would vary depending on the site and matrix conditions, and they suggest carrying out studies for each case to determine optimum amounts. Their experiment showed that for extractable pesticide reduction the compost addition was ineffective below 20% compost by weight. In their previous studies, much faster reduction of extractable pesticide rates had occurred at 50% compost. This indicates that higher than 50% compost would be beneficial for reduction purposes, while 20% would be a minimum compost addition for these

conditions.

Lilja et al. (1995) studied the biodegradation of PAH-contaminated soil using a slurry reactor test and a soil column test, and examined the effect of adding ground tree bark as a carbon source. The four slurry reactor tests were carried out in four 1000 mL glass reactors which were aerated (1 L min^{-1}) and agitated using mechanical agitation. The reactors were maintained at room temperature. In each reactor, 100 grams of the soil was agitated for 4 to 6 weeks. Each reactor was also supplied with nutrients, using NPK-, S-, Mg-, and Ca- nutrients. The slurry reactor tests showed, interestingly, that the addition of soil bark hampered the reduction of the extractable PAH compounds. The soil column testing used glass columns filled with the soil. For the samples which were mixed with bark, 20 percent bark by volume was added.

Lilja et al. (1995) concluded that the addition of bark increases the porosity of the soil mixture, increases the moisture retention capacity of the soil, and provides a large area for microbial attachment as well as a matrix for efficient PAH adsorption. It also gives the microbes a carbon source.

Joyce et al. (1998) composted PAH compounds in simulated municipal solid waste (MSW) compost, consisting of paper, yard and food wastes. The compost was contaminated to 15.2 $\mu g\ g^{-1}$ fluorene, 16.1 $\mu g\ g^{-1}$ of anthracene, 15.4 $\mu g\ g^{-1}$ phenanthrene, 17.1 $\mu g\ g^{-1}$ pyrene and 18.5 $\mu g\ g^{-1}$ benz[a]anthracene, for a total contamination of 82.3 $\mu g\ g^{-1}$ PAH compounds. Oxygen was supplied through a pumping system in amounts in excess of the calculated stoichiometric needs of the compost and was only supplied during the active composting stage, where the ambient temperature around the bioreactors was maintained at 50 °C. The reduction in extractable concentrations of the five PAH compounds was monitored separately. The anthracene, pyrene, phenanthrene, and

fluorene were all reduced significantly during the experiment to levels approaching 0 μg g^{-1} in each case. The benz[a]anthracene showed a definite difference in reduction compared to the other compounds, with a much slower removal of compound and also a higher level of residual extractable contamination than the other four compounds tested. It was unknown whether the removal of fluorene was due to volatilization, sorption, or biodegradation processes. The three composting-suitable compounds (pyrene, anthracene, phenanthrene) showed a significant drop in contamination within the first 6 days of the experiment. It was observed that the majority of the degradation of the compounds occurred within the active composting phase; little to no degradation occurred during the curing stage of composting.

Hupe et al. (1996) investigated the biological degradation of soils, trying to optimize the degree of degradation during their study. They investigated mixtures with soil:compost ratios (by weight) of 2:1, 4:1 and 8:1 at 22 °C. It was found that the oxygen consumption of the reactors decreased as the amount of compost decreased. Hupe et al. (1996) also monitored the effect of using compost additions of varying compost age; they observed that the reduction in hydrocarbons was independent of the age of compost used and the hydrocarbons were reduced by approximately 94% in all cases (after 60 days). This reduction was monitored through the extractable hydrocarbons present in the soil matrix, substrate-induced respirometry for the hydrocarbons present in the compost materials, production of carbon dioxide by the reactors, and volatile organic compound (VOC) analysis of the offgas to determine volatilization of hydrocarbons.

Diaz et al. (1995) showed that API separator oily waste could be composted. The compost mixture consisted of dewatered digested sludge, composted sewage sludge, and woodchips which was mixed with the oily waste to be composted. One reactor was a

control, where the compost mixture was autoclaved prior mixing with the oily waste. Composting occurred over a 33 day period and the rate of reduction was rapid in the first 13 days for the active (non-control) reactor. The downward trend in reduction paralleled the upward trend in temperature within the reactor. The removal rates observed were 2.5 to 5.5 times higher than removal rates with a landfarming operation on the same soil. The reactors were (by olfactory observations) assumed to be anaerobic.

Wischmann and Steinhart (1997) examined the formation of PAH oxidation products in jars with soil/compost mixtures kept at ambient temperatures. They determined that after 25 weeks, all PAHs within the jar filled with coal tar oil and soil were significantly degraded from original concentrations. However, most of the fused 3 to 4 ring PAH compounds showed no evidence of degradation. The residuals from the coal tar oil composting were acenaphthalene, flourene, phenanthrene, anthracene, fluoranthene, and pyrene. The jar containing coal tar oil, soil and compost (9:1 ratio of compost to soil by dry weight) showed that the PAHs were also significantly degraded. However, the fused 3 ring PAH compounds were all degraded to <3% of the original concentration by 25 weeks. The degradation of the PAH compounds was more complete in the soil/compost mixture. The addition of the compost aided in the degradation of even the previously recalcitrant 3 to 4 fused ring PAH compounds. They also observed that in the co-composting case, short-term maximums of the oxidation products of PAHs correlated fairly well with the periods of more rapid contaminant degradation.

The analysis of Kirchmann and Ewnetu (1998) indicated that the greatest decomposition of the oily wastes used in the experiment occurred during weeks 3 to 5. The oily wastes were added directly to horse manure. Their results indicate that pyrene, chrysene, and dibenz(a)anthracene were slightly recalcitrant. Also, they determined that

successive additions of manure caused the degradation of the compounds to be enhanced.

Kastner et al. (1995) used radiolabelled anthracene and hexadecane during co-composting of a sandy soil. $^{14}CO_2$ recovery was immediate for the hexadecane (1-^{14}C hexadecane)and reached 53.6% of original radioactivity at 103 days of co-composting. The anthracene (9-^{14}C anthracene) required a 12 day lag period, and after 103 days 23.6% of the original radioactivity had been recovered. They also determined that the majority of residue remaining in soil after 103 days was "bound" residue, unextractable by either organic acid or humic acid extractions.

5.3 LITERATURE SUMMARY

The literature on TNT composting indicates that the maximum soil:organic amendment ratio is approximately 30% by volume (Williams and Keehan, 1993). However, the soil type used in the experiment is unknown.

The literature on chlorophenol composting indicates that composting is an effective way to reduce chlorophenol concentrations. Valo and Salkinoja-Salonen (1986) used 64.8% contaminated soil and observed a significant decrease in chlorophenol concentration after one summer of composting the mixture in a windrow. Laine and Jorgensen (1997) used 82.4% contaminated soil in their composting mixtures and observed that after about 9 weeks the percent removal was quite high (approximately 80 to 98%).

Hydrocarbon compounds have also been shown to compost well. Diaz et al. (1995) showed that oily wastes could be composted by adding straight waste to a compost composed of dewatered sludge, composted sewage sludge, and woodchips. They found the rate of destruction fastest within the first 13 days of composting. Beaudin et al.

(1996) used 35.4% contaminated sandy soil (by weight) during composting and observed significant degradation. Joyce et al. (1998) used a PAH-contaminated simulated MSW compost mixture and achieved good reduction of extractable hydrocarbon results for pyrene, anthracene, fluorene and phenanthrene within the first 18 days of the experimental study.

Most of the experiments discussed above, when soil type was defined, used a sandy type of soil. Clay soils have inherent handling difficulties; their high moisture content, plasticity and tendency to aggregate cause difficulty in field conditions. Clay soils have much different material properties and behave much differently than a sandy soil. Since clay soils have a tendency to aggregate, it is postulated that the amount of clay soil that could be composted would be less than a sandy soil. This is due to the fact that the tendency to aggregate may reduce the FAS within the compost pile and affect oxygen transfer by acting to prevent oxygen flow. This may cause the microbial activity to slow down or cease at larger loadings of clay soil.

6.0 EXPERIMENTAL METHODS AND MATERIALS

The objective of the experimental study was to determine the maximum diesel contaminated clay soil loading that can be co-composted without adversely affecting the microbial activity of the compost system during the active composting phase. The microbial activity within the compost was measured as the relative heat generation of the compost and the volatile solids removal from the compost mixture. In order to determine whether the microorganisms were utilizing the diesel fuel within the clay soil as well as the carbon sources in the compost feedstock, a radiolabelled diesel compound (octadecane-1-^{14}C) was added to the soil and the respiration of ^{14}C from the reactors was monitored. The amount of total petroleum hydrocarbons was also measured in the feedstock. The composting reactors were operated under a compressive loading and were maintained aerobically by pumping air through the reactors at intervals of 5 minutes of every hour, to ensure that oxygen was not a limiting factor.

The experimental procedure was divided into three phases. The first phase characterized the feedstock materials. The second phase identified the compressive loading conditions to be used, and the third phase investigated the effect of increasing soil load on microbial activity.

6.1 INITIAL CHARACTERIZATION

The first phase of the experiment characterized the soil, biosolids, and woodchips used in the experiment. The results were used to create a "feedstock recipe" for

composting.

6.1.1 Soil Characterization and Preparation

The clay soil used in the experiment was previously characterized (Man, 1998). The soil was collected at depths of 3.0 to 4.5 m below surface from a site in Winnipeg, Manitoba. Representative samples were analyzed for BTEX (benzene, toluene, ethylbenzene, and xylenes) compounds. In order to determine whether the soil had been previously contaminated by hydrocarbons, total volatile hydrocarbons ($\leq C_9$), total semi-volatile hydrocarbons (C_{10} to C_{30}) and heavy extractable hydrocarbons ($>C_{30}$) were measured. Other analyses performed included carbon content, nutrients (N, P and K), metals content, grain size distribution, and general soil quality parameters. The soil characterization is summarized in Table 6.1.

Table 6.1: Soil Characterization Analysis Results from Man (1998)

Parameter	Units	Detection Limit	Sample Results
Hydrocarbons			
benzene	μg/g	0.04	<0.04
toluene	μg/g	0.04	<0.04
ethylbenzene	μg/g	0.04	<0.04
xylenes	μg/g	0.03	<0.03
total volatile hydrocarbons (C_{10}-C_{30})	μg/g	10	<10
total extractable hydrocarbons (>C_{30})	μg/g	5	<5
Carbon			
fraction of organic carbon - total	g/g	-	0.0028
inorganic carbon, total	g/g	0.0005	0.0194
carbon - total	g/g	0.001	0.0222
Nutrients			
total nitrogen	%	0.1	<0.1
phosphorous	μg/g	0.3	539
potassium	μg/g	2.0	8380
Grain Size			
sand	%	-	11
silt	%	-	3
clay	%	-	86
General Parameters			
pH	pH units	0.5	7.3
field moisture content	% (w/w)	0.1	17.4-25.3

6.1.2 Organic Amendments Characterization

Municipal biosolids and woodchips were used as the composting material for this experimental study. The biosolids were collected from the City of Winnipeg's North End Water Pollution Control Centre (NEWPCC) and consisted of primary and secondary sludges which had been anaerobically digested and centrifugally dewatered. Biosolids were collected and stored in a sealed, airtight plastic container at 4 °C to prevent moisture loss and to minimize decomposition of the biosolids. Before storing biosolids in airtight containers, the biosolids were gently and thoroughly mixed by hand and six 2 L beakers were filled with biosolids. The contents of each beaker were then spread evenly over a plastic sheet and quickly quartered to yield approximately 5 to 10 g quarters of which one was selected for analysis of volatile solids. A second sample was taken from each beaker and combined, then quartered, with three quarters chosen for analysis, to yield a total of 6 samples of biosolids for characterization. Three of the beakers, chosen randomly, were also sampled for nitrogen. Biosolids were stored in sealed ziploc bags at 4 °C until characterization was performed. The total volume of biosolids from which samples were taken was approximately 83 L.

Woodchips were created from brush trimming waste collected from the University of Manitoba's solid waste transfer and storage site at the Fort Garry campus. The wood was chipped using a Crary Bear Cat Limited model 70539 3 HP shredder, thoroughly mixed using a shovel for one hour, sieved to achieve particle sizes ranging from 2.4 to 9.6 mm, as recommended by Haug (1993), and was stored in airtight containers at 4 °C to prevent moisture loss and to minimize decomposition of the woodchips. After mixing the

woodchips with a shovel and before storing the woodchips in airtight containers, the woodchips were spread evenly over a 3.5 m by 3.5 m plastic tarp to approximately five centimetres depth. The woodchips were then quartered, and two quarters were placed in airtight containers. The remaining quarters were combined and spread evenly over the tarp. Quartering was performed until quarters approximated 100 g of woodchips. At this point, two quarters were combined and further quartered to yield approximately 5 to 10 g of woodchips per quarter, from which two samples were selected. The remaining two quarters were also combined and then quartered to yield 5 to 10 g of woodchips, from which two samples were selected. All samples were stored in sealed ziploc bags at 4 °C until analysis was performed. The total volume of woodchips from which samples were taken was approximately 400 L.

The amendment materials were characterized for moisture content (MC), volatile solids (VS), organic carbon (OC), and total Kjeldahl nitrogen (N). The particle size distribution of the woodchips was also determined.

The moisture content, total solids, fixed solids and volatile solids were determined using the APHA standard methods 2540 B, E and G. The standard methods 2540 B and E were used to examine the solids properties of the biosolids, while the standard method 2540 G was used to analyze the solid woodchips.

The particle size distribution of the woodchips was determined by sieving methods. A sample of the woodchips was collected as previously described and sieved to allow for a particle size distribution determination.

The nitrogen content of the samples was determined using a TKN, or total Kjeldahl nitrogen analysis method, based on the micro-kjeldahl analysis without pretreatment presented by Carter (1993).

The dry basis organic carbon (OC) content of the sample was calculated using Equation 6.1 (Haug 1993):

$$OC = \frac{1 - \%FS}{1.8} \qquad [6.1]$$

where FS is the fixed solids content of the sample on a dry basis (fractional value).

6.1.3 Organic Amendment Mixture Recipe

The biosolids and woodchips were mixed to produce an initial moisture content of 55% using:

$$\text{woodchips required (kg / kg)} = \frac{MC_{biosolids} - MC_{target}}{MC_{target} - MC_{woodchips}} \qquad [6.2]$$

where the amount of woodchips required is expressed as kg woodchips per kg of biosolids used in the mixture; $MC_{biosolids}$ and $MC_{woodchips}$ are the moisture content of the biosolids and woodchips respectively and MC_{target} is the target moisture content desired (55%).

The resulting C:N ratio of the recipe was calculated using:

$$C{:}N_{amendmentmix} = \frac{(N_b \times C{:}N_b \times TS_b) + (N_w \times C{:}N_w \times TS_w)}{N_b \times TS_b + N_w \times TS_w \times R} \qquad [6.3]$$

where N_b and N_w are the nitrogen contents of the biosolids and woodchips respectively (g dry weight); $C:N_{amendment\ mix}$, $C:N_b$, and $C:N_w$ are the carbon:nitrogen ratios of the amendment mixture, biosolids and woodchips respectively; TS_b and TS_w are the total solids (%) of the biosolids and woodchips, respectively, and R is the biosolids:woodchips ratio (kg kg^{-1}).

6.2 EXPERIMENTAL LOADING CONDITIONS

The biocell reactors used in this study were previously described in the literature (Larsen, 1999; Chen, 1998). The biocells were developed to simulate the compressive loading that occurs within a compost pile (Figure 6.1).

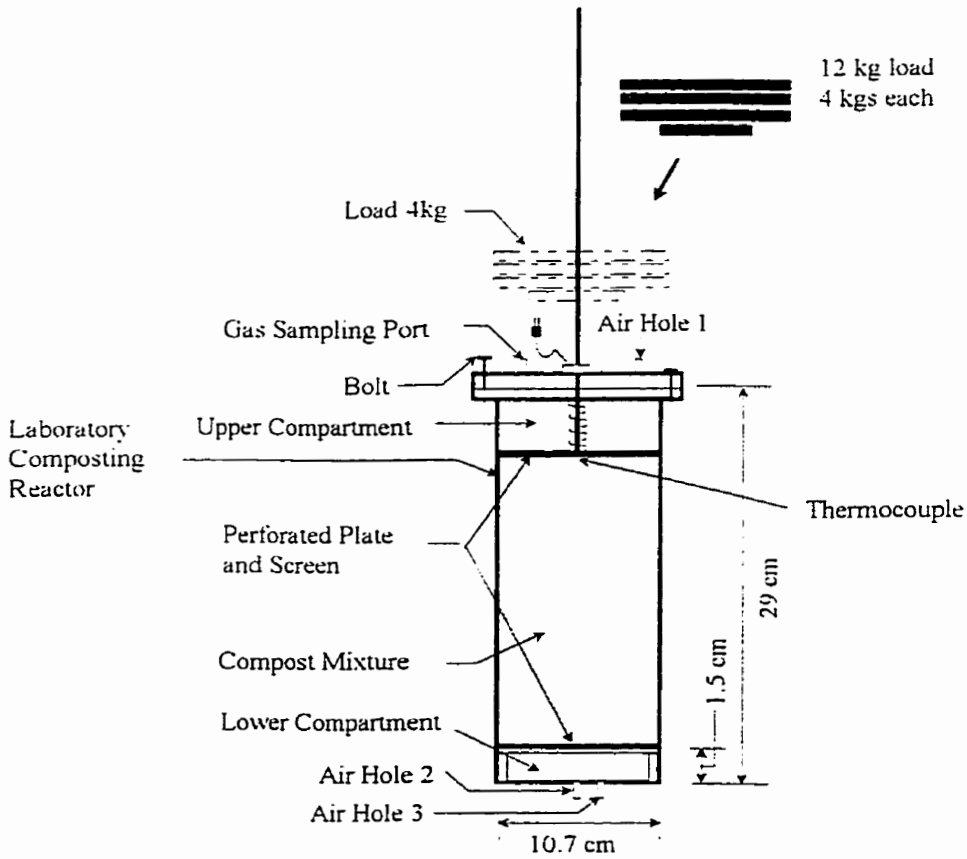

Figure 6.1: Schematic of Biocells Used for Testing; taken from Chen (1998)

The biocells were designed so that the loading was transferred to the compost through a perforated plate covered with a meshed screen (Figure 6.2). The screen prevented the compost mixture from extruding through the perforations in the plate, and the plate allowed the load to act over the cross-sectional area of the compost column.

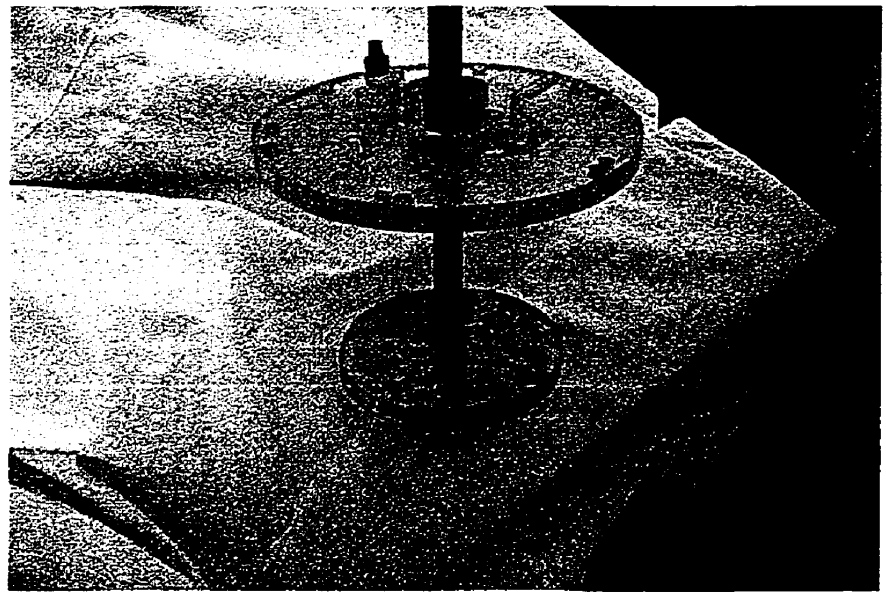

Figure 6.2: Cover of biocell, showing air hole and headspace testing vent, as well as perforated plate with mesh screen through which loading is applied

The lower end of the bioreactors also consisted of a removable perforated plate which was also covered with the meshed screen (Figure 6.3). The perforated plates allowed the air in the bioreactor to move freely through the entire cell. The biocell is shown completely in Figure 6.4.

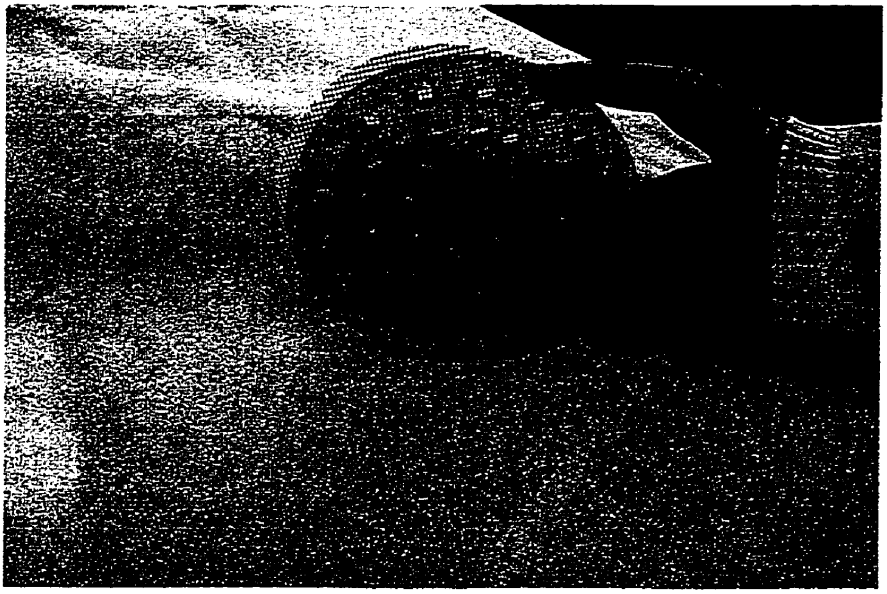

Figure 6.3: Perforated Plate with mesh screen from bottom of biocell

Figure 6.4: Complete biocell ready to be filled with cocompost

6.2.1 Loading Conditions Within Biocells

According to Tchobanoglous et al. (1993), minimal technology windrows (turned with a front-end loader) should be in the range of 3.05 to 3.66 m in height. NRAES (1992) suggests a height of 1.82 to 3.66 m for turning with a bucket loader. Using a windrow turning machine limits the height of the compost pile, at 1.52 to 2.44 m according to Tchobanoglous et al. (1993) and 0.91 to 2.74 m according to NRAES (1992). Because the addition of clay soil was anticipated to cause bulk density differences in the compost as well as potential handling difficulties, the low end of the height range was chosen. The numbers in the literature for a windrow turning machine indicate pile heights of 0.91 m or 1.52 m, as discussed above. The average of these heights. 1.22 m, was chosen for use in this study.

Using the bulk density of the compost, loading conditions for different pile heights can be obtained. Assuming no lateral stresses in the compost pile, the load on a point can be reduced to the load caused by the weight of compost above a point.

$$\text{Stress} = \frac{Wg}{A} \qquad [6.4]$$

where W is the weight of the compost (kg), g is the force of gravity (m s^{-2}), and A is the cross-sectional area of the biocell (m^2), and the stress is given in kPa. The weight can be calculated using the bulk density of the compost:

$$W = h\rho_{wb}A \qquad [6.5]$$

where h is the height of the compost above the point (m), and ρ_{wb} is the wet bulk density of the compost mixture (kg m^{-3}), and A is the cross-sectional area (m^2).

Combining the two equations, the stress can be calculated as follows:

$$\text{Stress} = \rho_{wb} g h \qquad [6.6]$$

6.2.2 Loading Conditions for Experimental Study

The basic stress equations discussed above were used to determine the loading conditions for the experiment. The first step of the loading condition phase was to determine the bulk density of a mid-range compost-soil mixture. This was accomplished by mixing three batches of compost with the same soil:compost loading rate. During the testing, it was determined that 600 g of organic amendment mixture fills a biocell. Each biocell was therefore filled with 600 g of compost and a corresponding amount of clay. In order to determine the loading conditions for the experiment, three mid-range (16% contaminated soil) mixtures were prepared. Each mixture was placed into a biocell of known cross-sectional area and weight. The height of the mixture was measured and was then used to calculate the volume of the mixture. The weight of the compost and biocell was then measured. The bulk density of the mixture (kg m^{-3})was calculated as follows:

$$\rho_{wb} = \frac{W_{cm} + W_c}{Ah} \qquad [6.7]$$

where W_{cm} is the weight of the biocell and compost mixture (kg), W_c is the weight of the biocell (kg), A is the cross-sectional area of the biocell (m^2), and h is the height of

the biocell (m).

Using the three biocells, the loading condition for the experiment was calculated as follows:

$$\text{Load (N)} = \frac{\rho_{wb} h g}{A} \qquad [6.8]$$

where ρ_{wb} is the wet bulk density of the mixture, measured at approximately 251.0 kg m^{-3}. The height of the pile above the biocell, h, is 0.8 m, while the force of gravity, g, is 9.81 kg m^{-1} s^{-2}. A is the cross-sectional area of the biocell, 0.00916 m^2. The height of the pile was determined as 0.8 m above the reactor top, in order to simulate a compost heap of 1.22 m. The loading on the biocell was calculated as 18.1 N or 1.85 kg. This calculated wet bulk density was used in the second step of calculating loading to determine the actual loading present for 0.8 m of compost acting on the reactor, by adjusting the experimental loading to reflect compression and density changes of the 0.8 m height over time.

The second step of experimental loading was to determine the loading change over time. The initial calculated load was applied to the biocell and allowed to compress the compost mixture for one hour. According to Chen (1998), one hour is the time where the maximum compressive effects occur. The change in height in the biocell was measured, and the corresponding change in volume was used to calculate a new bulk density, assuming that there was no weight change in the biocell. The new wet bulk density was used to calculate a new loading which was then applied to the biocell and allowed to compress the contents. These steps were repeated until there was less than 3%

difference between the new calculated load and the applied loading.

6.3 Effect of Soil Loading on Microbial Activity

The third phase of the experiment used the biocells to compost mixtures with different soil loadings. Using the information gained in the first two experimental phases, biocells were loaded with 2.25 kg weights and filled with 600 g of organic amendments, to which varying amounts of wet, diesel contaminated clay soil was added. The soil addition was based on percent wet weight, and ranged from 0 to 30% contaminated clay soil. A total of seventeen biocells were run during the experiment, one biocell at 0% soil loading, and one biocell each for soil loadings ranging from 4% soil to 30% soil (in 2% increments); one replicate each of the 28% and 30% soil biocells was also performed.

6.3.1 Compost Mixture Preparation

The woodchips, stored in five separate airtight containers, were sampled by obtaining two 2 litre samples from each airtight container, which were then combined, spread evenly over a plastic sheet, and quartered (if necessary) to yield adequate woodchips for addition to the biocells. The biosolids were sampled by collecting four stratified subsamples from the biosolids airtight storage container, which were then combined for use in the compost mixture.

The woodchips and biosolids were weighed, including an allowance for three 50 g samples for initial FAS measurements and dry bulk density testing, and placed on a clean plexiglass surface. The amendments were mixed thoroughly by hand on this surface.

Once the organic amendments were thoroughly mixed, the contaminated soil was added to the mixture.

The clay soil used in the experiment was prepared for the experiment by drying at 105 °C to a constant weight, and was broken using a hammer into aggregates to pass a ½" sieve. The soil was then brought to 50% moisture (dry basis) to approximate field conditions and then contaminated with diesel fuel to bring the contamination level to 5000 mg diesel fuel per kg of dry soil. To contaminate the soil, the necessary weight of dry soil (which varied per biocell) was added to a beaker. Water was added to bring the moisture content of the soil to 50% (dry basis). The diesel fuel, which had previously been spiked with octadecane-1-^{14}C (supplied by the Sigma Chemical Co., St. Louis, Missouri) was then added to the beaker, and gently agitated until the soil had absorbed the liquid. The mixture was then gently mixed by hand to distribute the water and diesel fuel evenly throughout the soil before adding it to the organic amendments.

Once the contaminated clay soil was added to the organic amendment mixture, samples for initial FAS and dry bulk density were taken, the co-compost was weighed to ensure initial weight was accurate, and the co-compost was then placed into the biocells for composting to begin.

6.3.2 BIOCELLS

In order to examine the effects of different contaminated soil loading rates on compost performance, the other variables of the composting process were controlled as much as possible. For this reason, each biocell contained the same amount of organic

amendment mixture, and therefore the same initial volatile solids content.

The biocells (shown in Figures 6.1 and 6.4) were placed in an insulating chamber as shown in Figure 6.5, which was used to maintain the temperature of each biocell separately.

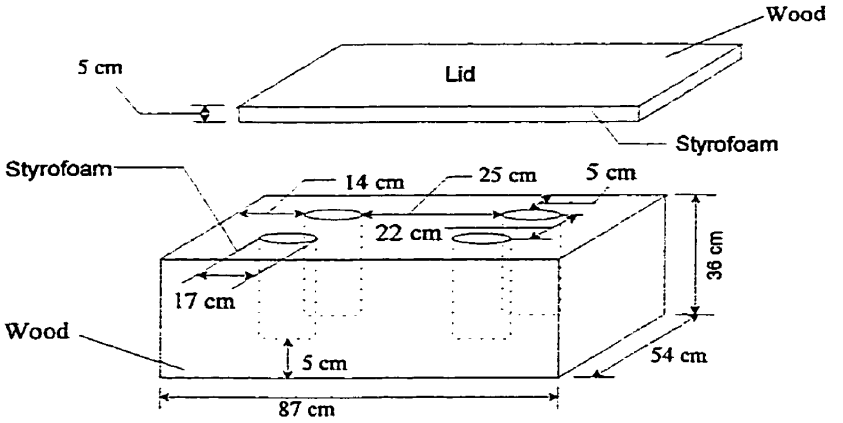

Figure 6.5: Schematic for insulating box for biocells; taken from Chen (1998)

The insulating box is shown in Figure 6.6 as it was constructed and used in this experimental study. Each biocell was also equipped with a thermocouple in order to measure the temperature within the compost mixture during the experiment.

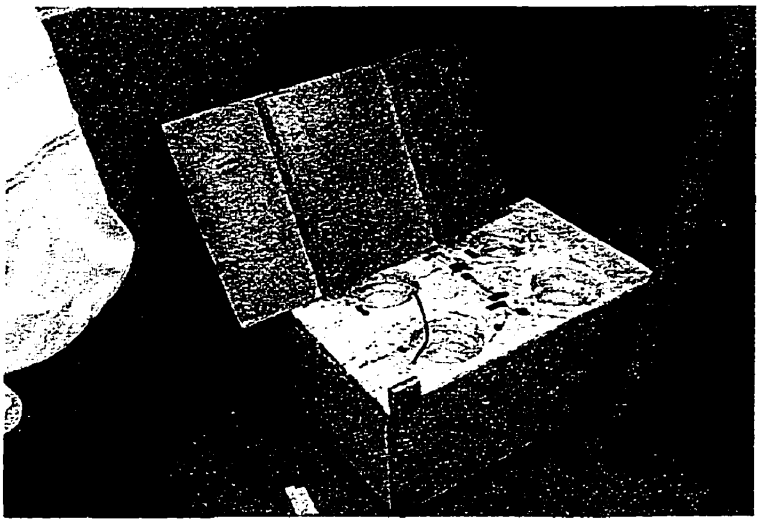

Figure 6.6: Insulating box for biocells

In order to prevent oxygen from becoming a limiting factor in the composting process, each biocell was connected to an air supply, through air hole 1 (Figure 6.1), which was hydrated to maintain the moisture content of the compost and minimize environmental disturbances. The air was also heated to the same temperature as the environmental chamber in which the insulating chamber was kept in order to minimize heat loss from the biocells, and was hydrated prior to passing through biocells in order to ensure that the air supply was not stripping moisture from the co-compost. The air supply was controlled by 600 rpm pumps by Cole Parmer Instrument Company and Masterflex speed controllers. The biocells were aerated for 5 minutes every hour at a rate of 18 mL per second. This rate was chosen by filling 4 biocells with varying soil:compost mixtures (0, 10, 20 and 30% soil). Each biocell was aerated for 5 minutes. The five minute aeration cycle used 18 mL of air per second, for a total of 5.4 L of air, enough to flush the entire volume of the biocell, at 2.5 L, at least twice. Headspace samples were taken every 30 seconds over the 5 minute span. The aeration rate was adjusted so that at the end of a 5 minute span, the headspace of each biocell was of the same composition as atmospheric air.

With the biocells in place in the insulating chamber and the air supply connected to each biocell, the air outflow from each biocell was collected through air hole 1 and bubbled through flasks containing NaOH. The flasks of NaOH acted as a volatiles trap. Since the radiolabelled octadecane, upon metabolism, was converted to $^{14}CO_2$, the NaOH traps were used to collect the respired ^{14}C for scintillation analysis. Calculations for the NaOH traps are found in Appendix D.

The biocells were loaded according to the conditions determined in experimental phase II (section 6.3.2). Once the biocells were loaded, the insulating chamber was placed into the environmental chamber (Figure 6.7).

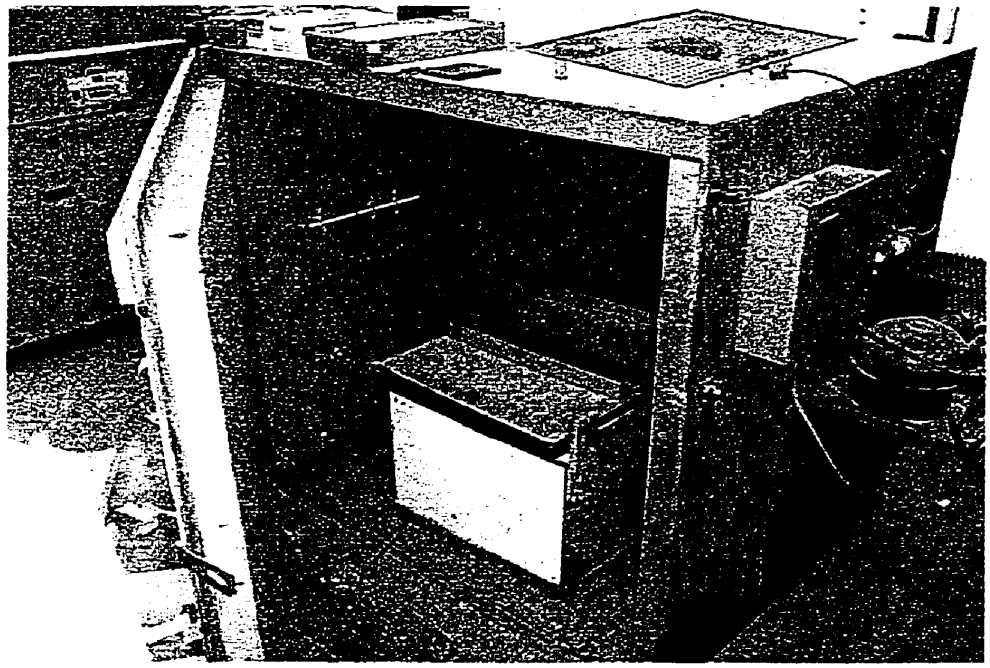

Figure 6.7: Environmental chamber, with insulating chamber inside

The temperature control chamber was used to control the loss of heat from the biocells. On Day 0 of testing, the temperature within the chamber was set at 35 °C, then ramped by 2 °C each day until the temperature reached 45 °C. The chamber temperature was kept at 45 °C for the remainder of the experimental run. The experimental run was considered complete when the biocell temperatures dropped to below 46 °C for 24 hours during the experiment, which would indicate that active co-composting had ceased and temperatures were beginning to be driven by the environmental chamber, or a total of 14 days had passed, whichever occurred first.

6.3.3 MONITORING OF MICROBIAL ACTIVITY

Six separate parameters were monitored during co-composting. The microbial activity within the biocells was monitored through the first three parameters; headspace analysis, relative heat generation and volatile solids removal. The compressive effects were observed through the fourth analysis, the FAS profiles of each biocell. The fate of the diesel fuel during composting was monitored using the final two analyses, $^{14}CO_2$ evolution and TPH concentrations.

6.3.3.1 HEADSPACE ANALYSIS

The headspace of each biocell was monitored for oxygen and methane concentrations. Biocells were analysed on days 0, 5, and 10 for oxygen and methane content. Headspace samples were taken by inserting a 1 mL syringe into the sampling port on the upper portion of the biocell. Headspace gas samples were measured by injecting the 1 mL headspace sample into a GOW MAC Model 550 gas chromatograph (GC) equipped with a Poropak Q 80/100 mesh column and a thermal conductivity detector. Standards containing known concentrations of oxygen and methane were used to calibrate the GC before sampling and after every seven samples. Headspace samples were taken approximately 0.5 hours before aeration, 1 minute before aeration, and every 30 seconds during aeration. Samples were taken during aeration to ensure that the headspace of the biocell approximated atmospheric conditions by the end of the aeration cycle.

6.3.3.2 Relative Heat Generation

As discussed previously, the environmental chamber maintained a set temperature profile during each experimental run. During each run, biocell temperatures were monitored at least twice daily using a Fluke K/J thermometer. Readings were taken when the temperature reading stayed constant for longer than 10 seconds.

The temperature monitoring results were used to generate temperature profiles for each soil loading. The profiles were used to calculate the number of degree-days above 35 °C in order to compare the relative heat generation of the different soil loadings. The degree-days were calculated by mathematically determining the area under each soil loading temperature profile to a datum of 35 °C. Assuming a straight-line relationship between measured temperature points, the area under the curve was determined as follows:

$$A = \left[\sum_{i=1}^{n} \frac{(T_i + T_{i-1}) * (t_i - t_{i-1})}{2} \right] - 35 * (t_n) \qquad [6.9]$$

where A is the area under the curve to the 35 °C datum (also equal to number of degree-days), T_i is the temperature at time t_i. In order to compare runs with differing lengths due to the temperature requirements (biocell must be at least one degree above chamber when chamber is at 45 °C, otherwise active composting is assumed complete), the area A was divided by the number of days per run for each soil loading.

6.3.3.3 VOLATILE SOLIDS REMOVAL

The volatile solids content of the final samples were determined according to the methods discussed in section 6.1.2. However, due to the highly organic nature of the samples, the samples were ashed over a burner and then placed into a muffle furnace in order to ensure that complete ashing occured.

Upon completion of the composting run, the biocells were removed from the temperature control chamber, and the contents were weighed and prepared for sampling. One biocell was opened at a time, and the contents of the biocell were quickly placed onto a plastic surface. The contents of the biocell were examined and the condition of the contents noted. The compost was then stored in a plastic bag at 4 °C until further analysis was performed. After all biocells had been examined, and the contents of the biocells were allowed to reach 4 °C, analysis was performed. The contents of a single biocell were removed from the ziploc bag and quickly mixed thoroughly by hand on a plastic surface. The mixture was then quartered to yield approximately 5 g samples, two of which were combined for TPH analysis. After quartering, the mixture was then ground using a clean coffee grinder. During the grinding care was taken to ensure that samples did not lose moisture and remained cool. After grinding, the compost was again placed in a ziploc bag and stored at 4 °C until sampling. Once the compost had cooled, it was removed from the bag and quartered to yield approximately 5 g samples, two of which were combined to create a single sample. The compost was mixed thoroughly, and quartered to yield a second sample. This procedure was repeated to yield a total of four samples for volatile solids analysis, and three samples for TPH analysis.

Microbial activity was monitored by determining the amount of volatile solids destroyed over the experimental run. The initial volatile solids content by weight of each biocell was the same, the initial and final mass of each biocell was recorded, and samples were taken from each biocell at the completion of composting to measure the final volatile solids content.

6.3.3.4 Effect of Soil Loading on Free Air Space (FAS)

The initial free air space (FAS) was determined using the methods described below. The method for determining FAS was created for soils, which are mostly inorganic substances. There is presently no method in existence for the determination of FAS (to the author's knowledge) for a heavily organic substance. The initial compost mixture was quartered to obtain approximately 25 gram quarters, two of which were combined for a single sample. The mixture was then requartered twice, to obtain a total of three samples for FAS analysis. The first step of this method was to determine the particle density of the compost mixture using the Pycnometer method (Klute et al. 1986). This involved the following steps:

1. Weigh a clean, dry 250 mL flask
2. Add approximately 50 g of compost to the flask, ensuring that the outside of the flask is clean after addition
3. Weigh the flask and compost
4. Fill the flask about half full with distilled water. Boil the mixture gently over a bunsen burner for several minutes, agitating the sample gently to prevent foaming.
5. Cool the flask to room temperature and add enough distilled water to fill the flask, drying the outside of the flask carefully.
6. Weigh the flask and contents. Determine the temperature of the contents.
7. Remove compost from flask, thoroughly clean and dry the flask. Fill flask

with distilled water at the same temperature as determined in step #6. Weigh the flask.

Using the readings taken during these steps, the particle density can be calculated using the following equation:

$$\rho_P = \frac{\rho_w (W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)} \qquad [6.10]$$

where ρ_p is the particle density (kg m^{-3}), ρ_w is the density of water (at the temperature measured, in kg m^{-3}), W_s is the weight of the flask plus dried compost sample (kg), W_a is the weight of the flask (kg), W_{sw} is the weight of the flask filled with compost and water (kg), and W_w is the weight of the flask plus water (kg).

In order to calculate the FAS, the bulk density of the compost mixture must also be determined. Samples were taken by quartering the initial compost mixture as described above. The dry bulk density was calculated using the Core method, taken from Carter (1993). The steps for this method are as follows:

1. Weigh 100 mL clean dry glass beaker
2. Place compost sample (approximately 25 to 50 g) in beaker. Weigh beaker and compost.
3. Place sample in a drying oven at 105 °C. Dry completely.
4. Weigh the beaker and dried compost.

The dry bulk density can be calculated using the following equation (Carter, 1993):

$$\rho_{db} = \frac{W_{dc} - W_c}{V} \qquad [6.11]$$

where ρ_{db} is the dry bulk density of the compost (kg m^{-3}), W_{dc} is the weight of the dried compost and container (kg), W_c is the weight of the container (kg), and V is the volume of the compost sample (m^3).

The total porosity of the compost can then be calculated using Equation 6.12:

$$n = 1 - \frac{\rho_{db}}{\rho_p} \qquad [6.12]$$

where n is the total porosity of the compost (unitless), ρ_{db} is the dry bulk density of the compost (kg m^{-3}) and ρ_p is the particle density of the compost (kg m^{-3}).

The volumetric water content of the compost sample can be calculated as:

$$\theta = \frac{MC \cdot \rho_{db}}{\rho_w} \qquad [6.13]$$

where θ is the volumetric water content of the compost (unitless), MC is the moisture content of the compost (%), ρ_{db} is the dry bulk density of the compost (kg m^{-3}), and ρ_w is the density of water (kg m^{-3}).

The FAS of the sample can then be calculated using equation 6.14:

$$FAS = n - \theta \qquad [6.14]$$

The method of testing for FAS was not designed for organic substances. It is difficult to load the flasks used for testing (see section 6.3.3) at the same level of compaction, which can alter the FAS of a compost mixture significantly. Also, the test was designed for inorganic substances (soil), and does not account for the possible absorption of water by organic substances, or for the effect of boiling the water when

testing organic substances.

The change in FAS was measured by observing the height change of the compost mixture within the biocell. Change in FAS was calculated through the assumption that any volume loss during co-composting was due to a loss of FAS.

6.3.3.5 TPH DATA METHODS

At the start of the experiment, the soil was analyzed separately for hydrocarbons to ensure that the method of diesel addition was adequate. The biosolids and woodchips used in the experiment were also tested for presence of hydrocarbons in the range of interest. The TPH values were determined in accordance with the protocol set out in the Environmental Engineering Department Diesel Fuel in Soil Method (1996). Hydrocarbons were extracted from soil samples according to USEPA Method 8015B using a hexane-acetone extractant, and the resulting extracts were analyzed in an Hewlett Packard 5890 gas chromatograph. The chromatograph was equipped with a flame ionization detector and packed column injector, and the integration was performed using a Waters model 740 data module. A 15 m X 2.65 μm film thickness, HP-1, 0.53 mm cross-linked methyl silicone gum column was used with hydrogen as a carrier gas and nitrogen as the make-up gas. The temperature program was started at 100 °C for 1.5 minutes then ramped at a rate of 12 °C min^{-1} for 5 minutes. The method was used to determine hydrocarbons in the range of C_{10} to C_{19}. The method was also applicable to the organic compost mixture with the omission of the anhydrous sodium sulphate addition. All samples were analyzed in triplicate.

6.3.3.6 $^{14}CO_2$ DATA METHODS

The gas produced in the biocells was bubbled through 250 mL flasks filled with 200 mL of 2.0 M NaOH to convert the collected CO_2 and $^{14}CO_2$ into CO_3^{2-} and $^{14}CO_3^{2-}$, respectively. Calculations and assumptions for the strength of NaOH necessary in traps is included in Appendix C-6. From each trap, 0.1 mL of the NaOH was transferred into a new 7 mL scintillation vial containing 5 mL of liquid scintillation cocktail (EcoLume™, ICN Biomedicals, Costa Mesa, CA) in triplicate. Each vial was capped, labelled and gently agitated. The vials were stored in a dark room for 24 hours before scintillation counting in order to reduce the effects of chemoluminescence on the results. The samples were measured using a Beckman LS 7500 liquid scintillation counter using a program that corrected for quenching through comparing samples and quench standards to an internal radiation source. Measurements were recorded in disintegrations per minute (DPM), and were corrected for dilution and background radioactivity. Details of the methodology of using radiorespirometry methods and liquid scintillation counting were found in Coleman and Fry (1991) and Wang et al. (1975).

7.0 EXPERIMENTAL RESULTS AND DISCUSSION

The objective of the experimental program was to determine the effect of soil loading on microbial activity. The data collected during the experiment is present in complete form in Appendices A, B and C. The results will be summarized in the following sections.

7.1 INITIAL CHARACTERIZATION

Phase I of the experimental program was the characterization of the biosolids and woodchips used during the experiment in order to allow feedstock recipe calculations.

7.1.1 SOIL CHARACTERIZATION

The soil characterization was completed by Man (1998). The soil analysis indicated that the hydrocarbon parameters of the analysis (BTEX, total volatile hydrocarbons, total extractable hydrocarbons) were all below the detection limits of the laboratory method of analysis. This indicates that the soil was not previously subject to hydrocarbon impacts. The organic carbon and total nitrogen analyses showed that the levels of both parameters were negligible, at 0.28% and <0.1%, respectively. The grain size analysis indicated that the soil was a typical Winnipeg area glacio-lacustrine clay.

7.1.2 ORGANIC AMENDMENTS CHARACTERIZATION

The results of the characterization of the biosolids and woodchips are summarized in Table 7.1. Raw results are available in Appendix C.

Table 7.1: Characterization Results for Biosolids and Woodchips

Parameter	Woodchips			Biosolids		
	# of samples (n)	mean	% relative standard deviation	# of samples (n)	mean	% relative standard deviation
MC (% wb)	5	41.3	5.2	6	68.6	0.35
VS (% db)	5	68.2	4.6	6	38.6	1.1
OC (% db)	5	37.9	4.6	6	21.5	1.1
TKN (% db)	3	0.39	15	3	3.11	3.0
C:N ratio	-	97.2	-	-	6.91	-

The mean moisture content of the woodchips was 41.3% (percent relative standard deviation (% RSD) of 5.2%), indicating that the woodchips were likely created from freshly cut trees, as older, air-dried trees would generally produce woodchips with a lower moisture content. The carbon content of the chips indicates that the woodchips provide a source of carbon for microbial utilization. The fairly low nitrogen content of the woodchips is offest by the higher nitrogen content of the biosolids, which also have a high moisture content. The high moisture contents are ideal for creating a composting recipe; moisture levels should be approximately 55%, and ideally a mixture should be created which does not require the addition of water to maintain an initial moisture content in the range of 50-60%. The results of the testing are compared to literature sources in Table 7.2.

Table 7.2: Woodchips and Biosolids Characterization Results Compared to Literature

	Wytrykush (2000)	Chen (1998)	Tchobanoglous et al (1993) range (typical)	NRAES (1992) (typical)	WEF (1995)
Woodchips					
organic carbon, (% dry weight)	37.9	53.78	48.1		
nitrogen (% dry weight)	0.39	0.65	0.1	0.04-0.23 (0.09)	
C:N ratio	97.2	82.74		212-1313 (641)	271
moisture content (%)	41.3	12.56	15-40 (20)		
Biosolids					
organic carbon (% dry weight)	21.46	24.26			29.52
nitrogen (% dry basis)	3.11	3.11	1.6-6.0	2-6.9 (1.9)	1.88
C:N ratio	6.9	7.80	15.7	5-16 (16)	15.7
moisture content (%)	68.56	74.33		72-84	

Table 7.2 shows that significant differences existed between the woodchips used by Chen (1998) and the woodchips used here. The difference is due to a number of factors. The age and type of trees chipped in both experiments is unknown, and can affect the composition of the woodchips. Chen (1998) also air-dried woodchips before use and testing, whereas the woodchips used in this experiment were chipped and then immediately stored in an air-tight container at 4 °C in order to maintain the freshness and moisture content of the woodchips. The results for the woodchips are within the reported

results in the literature. The biosolids results are comparable to Chen (1998), although the moisture content is slightly less than reported in literature sources.

7.1.3 Organic Amendment Mixture Recipe

Using the results from the characterization, the organic amendment recipe was created. This "recipe", or combination of organic amendment materials, was used in each biocell to maintain optimum composting conditions for the experiment. The recipe was created using the equations given in section 6.2.2, and was designed with a moisture content of 55%, within the acceptable range of moisture content for composting as discussed in Chapter 5. The compost recipe is summarized in Table 7.3.

Table 7.3: Compost Recipe Parameters

	C:N ratio	% N (db)	ρ_b (kg/m^3)	kg of amendment per kg mixture (kg)	%TS (wb)	% VS (db)	VS (kg)
biosolids	6.9	3.11	1167.55	0.502	31.4	38.63	0.0610
woodchips	97.21	0.4	102.95	0.498	58.7	68.18	0.1974
compost	24.26	1.35	251.93	-	45.0	57.81	0.2584

Table 7.3 indicates that the compost mixture had 258.4 g of VS per kilogram of wet compost mixture. Each wet kilogram of mixture was composed of 502 g of biosolids, and 498 g of woodchips. The final mixture had a C:N ratio of 24.26, which is within the acceptable range of C:N ratios for composting.

7.2 EXPERIMENTAL LOADING CONDITIONS

The second phase of the experiment involved determining the loading conditions that were used within the biocells, as was discussed in section 6.3. The results of the loading are shown in Table 7.4.

Table 7.4: Iterative Loading Results

Load Calculated			
	Newtons		kilograms
	21.98		2.24
	22.08		2.25
	22.19		2.26
Mean:	22.08	Mean:	2.25
%R.S.D.[1]	0.388	%R.S.D.[1]	0.363

[1]%R.S.D. is the percent relative standard deviation of the results

The results of the iterative loading show that the compost recipe chosen compresses consistently, giving results within 0.4% relative standard deviation. The initial calculated loading was 18.1 N or 1.85 kg, with the mean final loading as an increase of 22% over the initial calculated loading. The soil loading used during the iterative loading process was a mid-range load (16% contaminated soil) in order to represent a typical loading condition. Using the results of the iterative loading, each biocell was loaded with 2.25 kg.

7.3 EFFECT OF SOIL LOADING ON MICROBIAL ACTIVITY

Table 7.5 shows the initial contents of each biocell. Each biocell was prepared with the same amount of compost in order to have a consistent volatile solids content in

each reactor and to ensure that the reactors were filled to approximately the same amount to minimize experimental bias. The clay soil was added in increasing increments, starting with the initial case of 0% soil, to determine the baseline volatile solids reduction and heat generation in unloaded compost. Loading of soil began at 4% contaminated clay soil (by weight) and increased in increments of 2% contaminated soil by wet weight. Diesel was added in amounts equalling 5000 mg kg^{-1} dry clay soil to ensure that levels of contamination were consistent for the soil.

Although the addition of diesel increases the amount of volatile solids in the reactors, the amount of volatile solids in each biocell from the compost mixture was 156.1 g, and it can be seen from Table 7.5 that the addition of diesel was insignificant in terms of volatile solids content and weight of the biocells. For this reason, volatile solids calculations were performed using the initial 156.1 g of volatile solids as initial volatile solids content for each biocell.

Table 7.5: Contents of Biocells

Contaminated Soil Loading	Amount of Components (g)		
%	Clay	Diesel	Total Weight
0	0.00	0.000	600.0
4	25.00	0.083	625.1
6	38.30	0.128	638.4
8	52.17	0.174	652.3
10	66.66	0.222	666.9
12	81.82	0.273	682.1
14	97.68	0.326	698.0
16	114.3	0.381	714.7
18	131.7	0.439	732.1
20	150.0	0.500	750.5
22	169.2	0.564	769.8
24	189.5	0.632	790.1
26	210.75	0.703	811.5
28	233.25	0.778	834.0
30	257.1	0.857	858.0

7.3.1 Relative Heat Generation Results

The temperature monitoring data for each soil loading biocell is included in Appendix C-2. The daily temperature measurements were used to generate temperature profiles for each soil loading rate, and were used to determine the relative heat generation over the experimental run. Temperature profiles for each biocell can be found in Appendix C-2.

7.3.1.1 TEMPERATURE PROFILES

The rise in temperature observed during the composting process reached a maximum over a range of 4 to 5 d for lower soil loadings, and 7 to 8 d towards the higher soil loadings; above 26% contaminated soil, temperature profiles were generally lower than lower soil loadings. The 0% soil loading biocell had temperatures greater than the chamber shortly after the start of the experimental run. The biocell temperature remained elevated, until approximately day 5, when the temperature dropped to a plateau, where it remained for the remainder of the experimental run, as shown in Figure 7.1

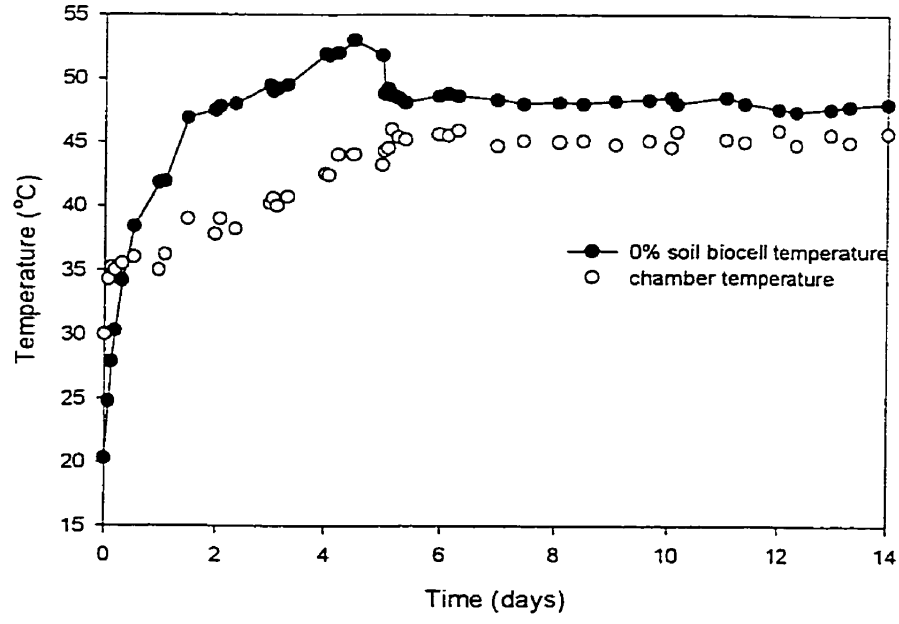

Figure 7.1: Temperature profile for 0% soil loading biocell with environmental chamber temperature profile shown

Temperature profiles of some biocells were affected by fluctuations in the environmental chamber temperature, seen in Figure 7.2, the temperature profile measured in the 4% soil biocell. Spikes in the biocell temperature profile match the slight spikes in the chamber temperature; other biocells that were in the chamber during this run (6, 26, and 30b% soil loading) also exhibited the same spikes. The same effect is observed in the 8% soil loading biocell, with a single spike occuring at approximately day 4. Profiles for the 6, 26, 30b, and 8% soil loading biocells are found in Appendix C-2.

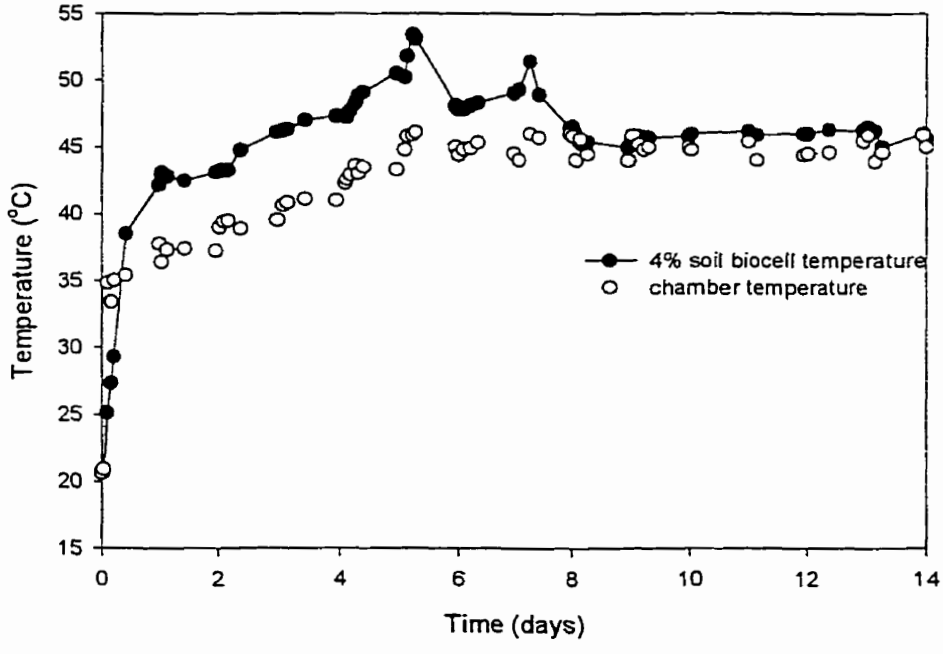

Figure 7.2: Temperature profile from 4% soil loading biocell with environmental chamber temperature profile shown

Although the spikes in the chamber temperature appeared to affect the biocell profiles for 4,6,26 and 30% soil, spikes in the chamber temperature did not affect all reactors similarly; chamber temperature spikes are seen in biocells with 12, 18, 22 and 24% soil on approximately day 8; these biocells were completed in a single experimental run and the chamber temperature spike is not reflected in the biocell temperature. Figure 7.3 shows the biocell and chamber temperature profiles for the 18% soil biocell, with the chamber temperature spike at approximately day 8 present.

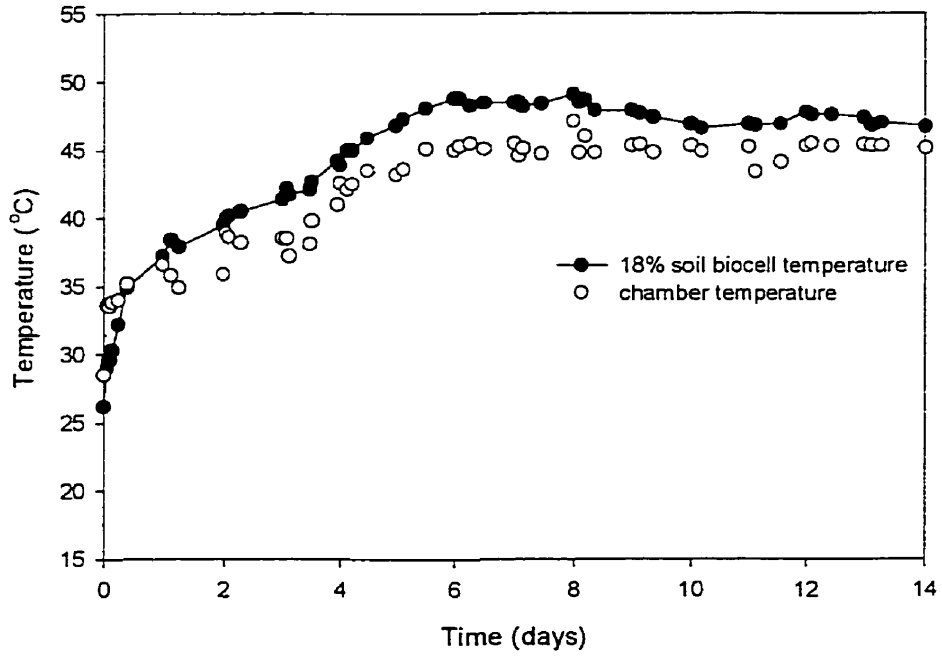

Figure 7.3: Temperature profile of 18% soil loading biocell with environmental chamber temperature profile shown

The initial profile observed for 0% soil was observed in other soil loadings; however temperatures reached by biocells generally decreased as soil loading increased, seen in temperature profiles in Appendix C-2. Biocells with high soil loadings (28 and 30%) had temperature profiles that were either slightly above or below chamber temperature, seen in Figure 7.4. The temperature profile for the 28a% soil loading biocell also shows the shortened experimental run for this biocell. Biocells were required to be at least one degree above the chamber temperature once the chamber temperature reached a plateau at 45 °C; otherwise, it was deemed that active co-composting had ceased and the run was terminated.

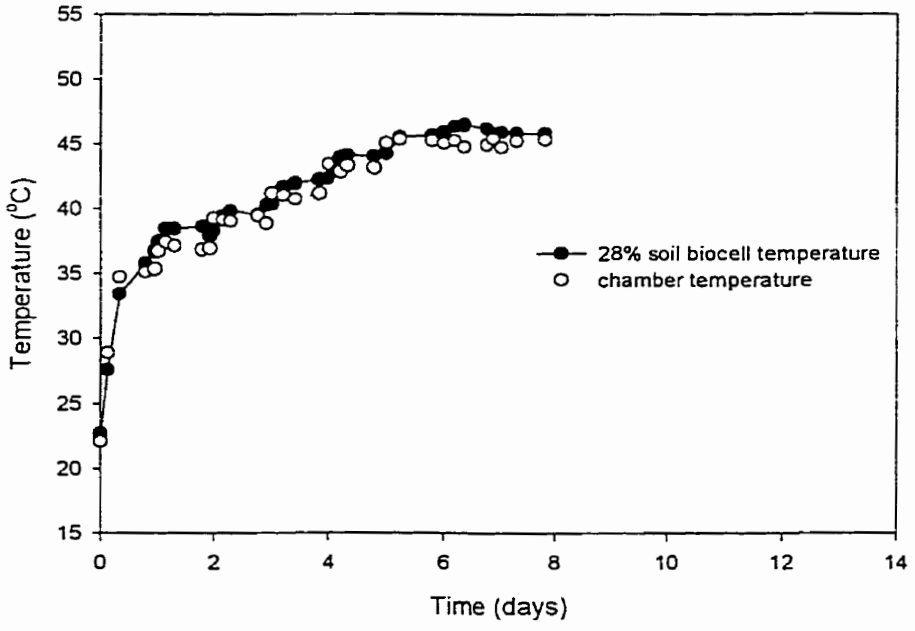

Figure 7.4: Temperature profile of 28%a soil loading biocell with environmental chamber temperature shown

7.3.1.2 DEGREE-DAYS ABOVE 35 °C

Using the temperature profiles and data, the heat generation (measured as degree-days per day above 35 °C) over the experimental run was calculated for each soil loading. Due to the differing experimental run lengths, the method of Larsen (1998) could not be used. The degree-day calculations are included in Appendix C-2 on the data sheets for each soil loading, and the results are shown graphically in Figure 7.5. Originally, the degree-days calculation was simply a sum of total degree-days above 35 °C, however, due to the differing experimental run lengths, it was felt that using this method introduced a bias to the results, as the comparison between biocells did not account for the number of days over which the temperatures were generated. Several different methods of analysis were examined and attempted; the final method used, with results presented in Figure 7.5, was to take the total number of degree-days generated per biocell over the experimental run, and then divide this total by the number of days in the experimental run for each biocell, as discussed previously in section 6.3.3.2. Using this method, each biocell is compared using the total degree-days generated and the days over which the experiment runs is also considered. Figure 7.5 shows the results of the relative heat generation analysis.

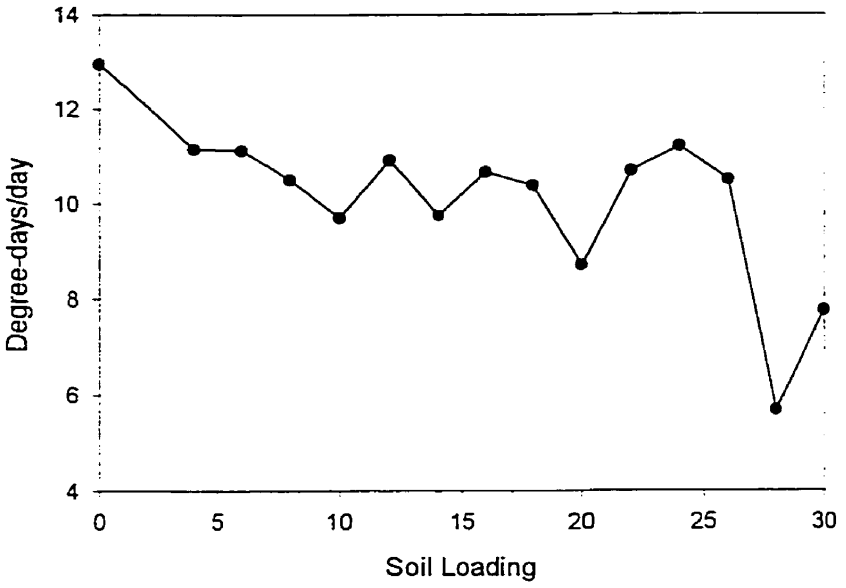

Figure 7.5: Effect of soil loading on relative heat generation expressed as degree days per day above 35 °C

The figure shows that the heat generation is highest at 0% soil loading, indicating that the addition of soil impacts heat generation even at low loadings (4%). The heat generation drops to a plateau of approximately 10 degree-days day^{-1} above 35 °C, where it remains until approximately 26% soil loading, when the heat generation begins to drop dramatically to approximately 6 degree-days day^{-1} above 35 °C. At lower soil loadings, high relative heat generation indicates that the composting process generates significant amounts of heat, similar to the heat generated at 0% soil loading. The drop in heat generation once soil has been added to the biocells indicates that the clay soil is impeding biodegradation of the

organic amendment mixture. The flattening of the curve indicates that the soil addition only impedes biodegradation beyond a threshold value, seen here as approximately 20% soil loading. The sharp decrease which occurs at 28% soil indicates that at this point the composting system is beginning to generate significantly less heat, possibly indicative of anaerobic conditions within these biocells. The results for 20% contaminated soil loading indicate that this data point may be an outlier, possibly due to experimental difficulties with this biocell during the experimental run, including maintaining air supply and off-gas tubing, as the tubing began to crack during the experimental run and was repaired temporarily.

7.3.2 VOLATILE SOLIDS REMOVAL

The volatile solids (VS) at the beginning of the experimental run were asssumed to be the same for all biocells, at 156.1 g of volatile solids from the biosolids and woodchips. The results from the testing are presented in Appendix C-3. The results from the testing were converted to a final weight of volatile solids, using the analytical results for volatile solids as a percentage and applying this to the final compost weight, measured at the end of the experimental run. This final weight of volatile solids was then compared to the initial weight of 156.1 g VS in each biocell at the beginning of the experimental run. This comparison was performed in order to calculate the percentage removal of VS from each biocell. These results are presented graphically in Figure 7.6.

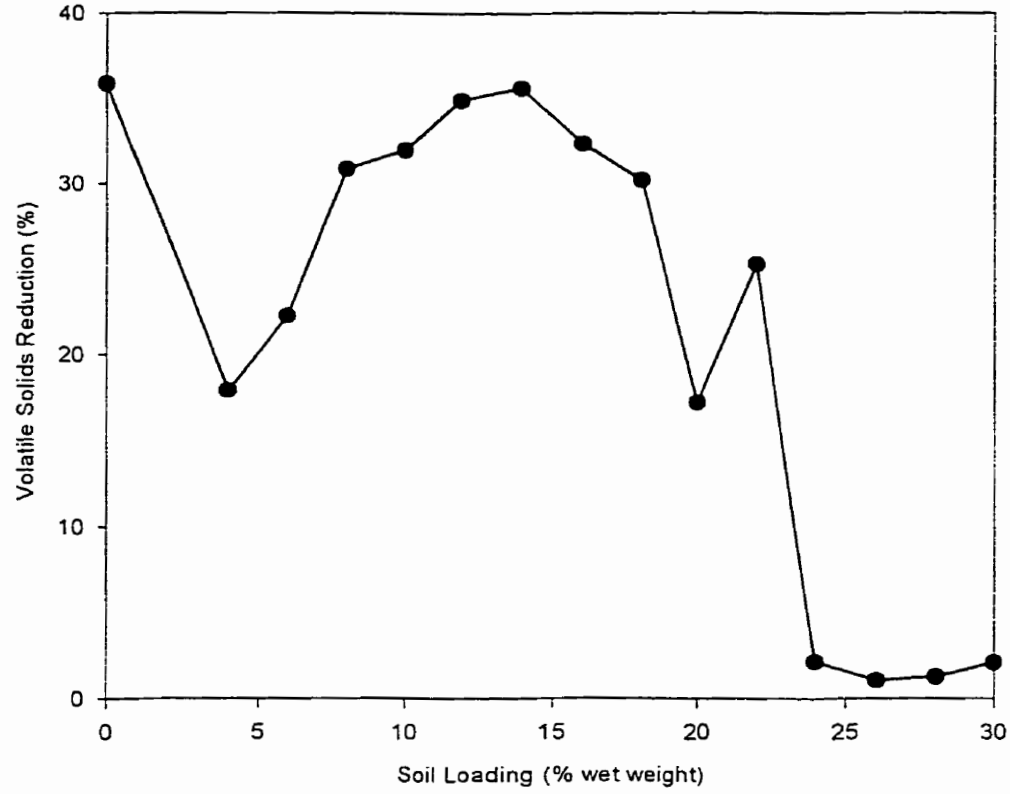

Figure 7.6: Effect of soil loading on volatile solids reduction expressed as percent volatile solids reduction

The soil loading rate affected the volatile solids reduction substantially at the lower end of the experimental loading condition, as well as at the upper limit of the loading conditions. The drop in volatile solids reduction beyond 24% soil indicates that beyond this level, the microbial community had more difficulty degrading the biodegradable fraction of the compost mixture. Once again, the 20% contaminated soil loading data point appears to be an outlier. In general, the data indicates that the composting process remained healthy until approximately 24% contaminated soil when

the volatile solids reduction dropped dramatically. The reduction in volatile solids is indicative of the microbial activity; the drop in volatile solids reduced indicates that the microbial activity levels were beginning to drop beyond approximately 24% contaminated soil. The maximum mean volatile solids reduction was 35.8%, which occured for 0% contaminated soil loading.

7.3.3 HEADSPACE ANALYSIS

Results of headspace testing are included in Appendix C-4. In all biocells, the day 0 results indicated that sufficient oxygen transfer was occuring to produce atmospheric conditions in the headspace of the biocells for all soil loadings both before and during the five minute aeration cycle. However, headspace analysis on subsequent days showed that above approximately 26% contaminated soil, the biocells became anaerobic. Both the 28% soil and the 30% soil biocells were run in duplicate, with anaerobic conditions occurring for both replicates. Biocells began showing levels of methane above 5% within the headspace of the 28% and 30% contaminated soil biocells on day 5 of the experimental run, as shown in Figure 7.7. Levels of methane below 5% were detected within biocells from 22% to 26% soil loading, as seen in the figure.

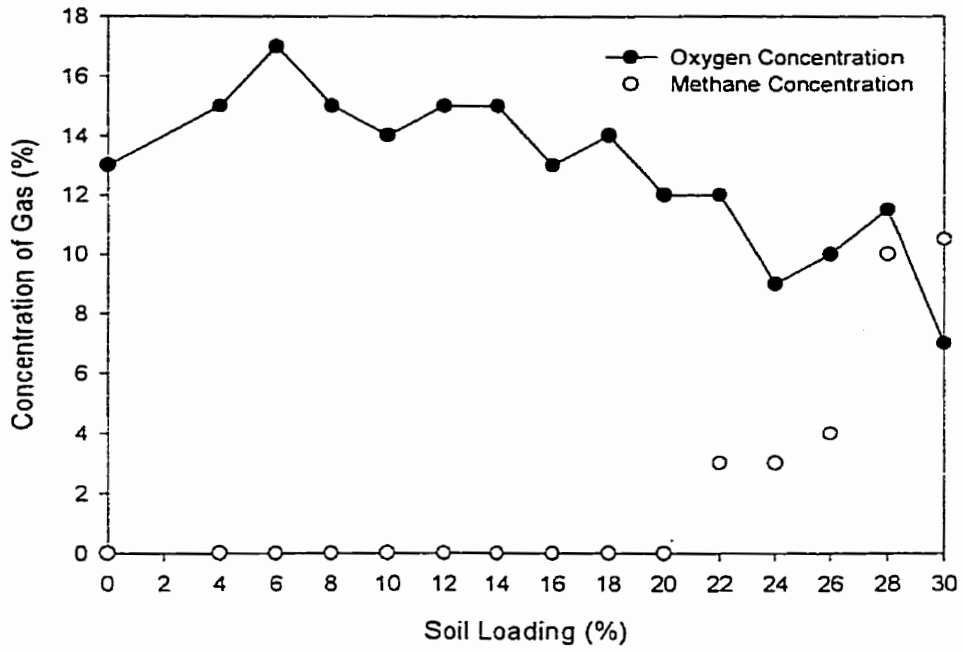

Figure 7.7: Oxygen and methane concentrations in headspace taken one minute prior to aeration cycle on day 5 of experimental run

The headspace analysis was the initial indication of the aerobic or anaerobic nature of the biocell, and anaerobic conditions were confirmed through odours noted by author at the conclusion of experimental runs. Other than the 28% and 30% soil biocells, biocells did not show the presence of methane levels over 5%, although the day 10 headspace analysis showed decreasing levels of oxygen in biocells (Figure 7.8).

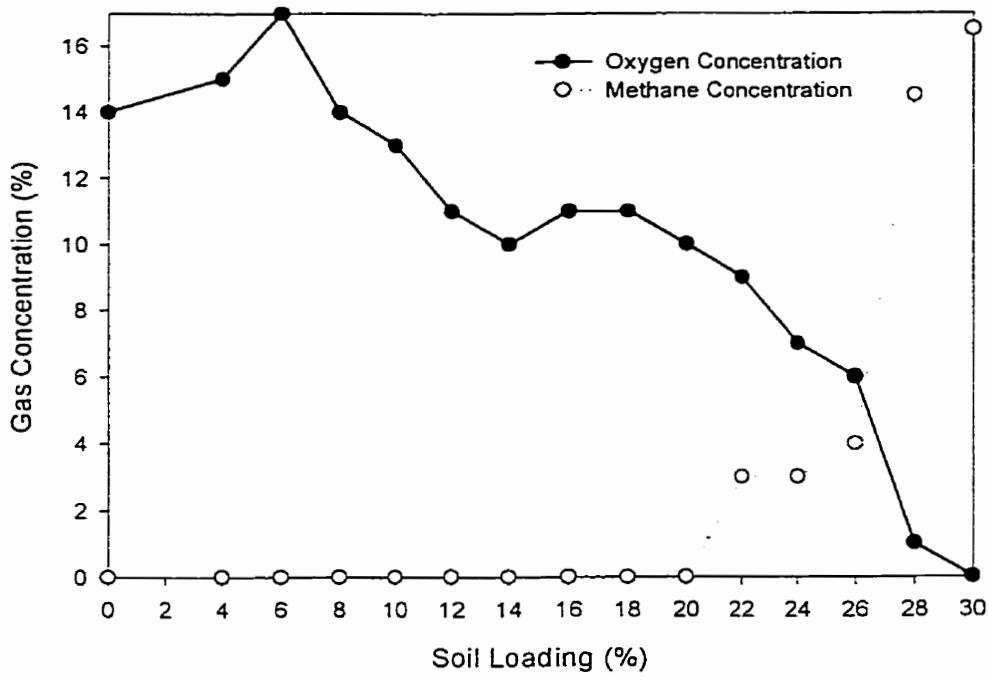

Figure 7.8: Oxygen and methane concentrations in headspace taken one minute prior to aeration cycle on day 10 of experimental run

This indicates that the composting system remained aerobic, with headspace oxygen levels above 5%, until approximately 26% soil. This was the maximum soil loading which maintained aerobic conditions during the composting process for this experimental design. It should be noted that the maximum aerobic soil loading condition is expected to change as experimental conditions are altered, and that without replicates of data points, the 26% contaminated soil loading aerobic threshold is an estimation. Also, oxygen levels in the biocells above 20% contaminated soil loading experienced a drop in oxygen levels for the pre-aeration cycle samples. However, no methane was observed in the headspace in levels

above 5% by volume. This is supported by Hupe et al. (1998), who reported that oxygen levels below 10% impede mineralization of diesel fuel, indicating that although aerobic conditions are maintained, the lower oxygen levels affect the amount of microbial removal of volatile solids, and the amount of microbial activity which causes heat generation. Olfactory and visual inspection of the biocells above 26% contaminated soil loading indicated that anaerobic conditions did not appear to be present throughout the biocell, but appeared to occur in pockets of anaerobic or aerobic activity. This was due to the structure of the compost; when the free air space compresses, the air supply will preferentially flow through the paths of least resistance, leaving anaerobic pockets. The anaerobic conditions above 26% contaminated soil and decreasing levels of oxygen observed in biocells above 20% contaminated soil was likely due to the increasing amount of clay soil coating the carbon source (woodchips). The clay was present in the compost matrix as both discrete particles (nuggets) and also as a clayey film that coated the woodchips as did the biosolids. The nuggets may have presented obstacles to air flow, creating pockets of anaerobic activity, while the clayey film coating the woodchips may have acted to inhibit degradation of the woodchips.

Although the aeration system was set up to flush approximately twice the volume of the biocell, aeration results indicate that for biocells with 28 and 30% soil loading, the aeration cycle did not act to flush the biocell. Figure 7.9 shows the aeration cycle acting to flush the biocell gas contents for the 22% soil biocell; although methane is initially present within the biocell, during aeration the methane is flushed and the biocell headspace approximates atmospheric conditions at the conclusion of the cycle.

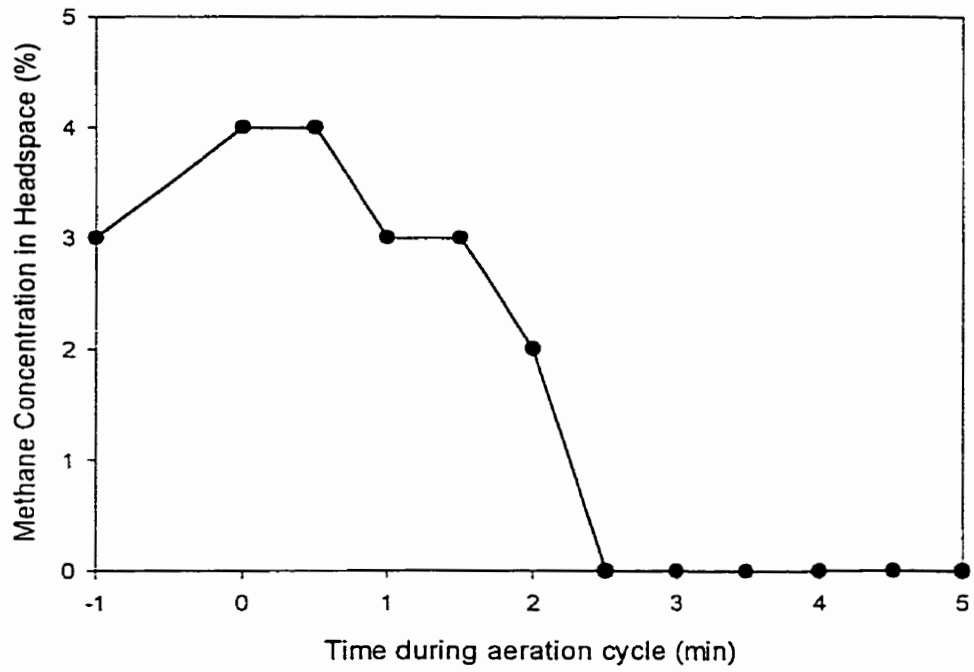

Figure 7.9: Methane concentration of 22% soil biocell on day 10 of experimental run during aeration cycle; includes measurement taken one minute prior to aeration

Figure 7.10 shows the aeration profile for the 28%a soil loading biocell; methane is present at the conclusion of the aeration cycle in the same concentrations as were present prior to aeration; this indicates that the biocell gas contents are not being flushed during aeration, indicating a blockage within the biocell or a failure of the aeration system. However, a failure of the system is unlikely; the same general results were observed for the 28%b, 30%a and 30%b biocells.

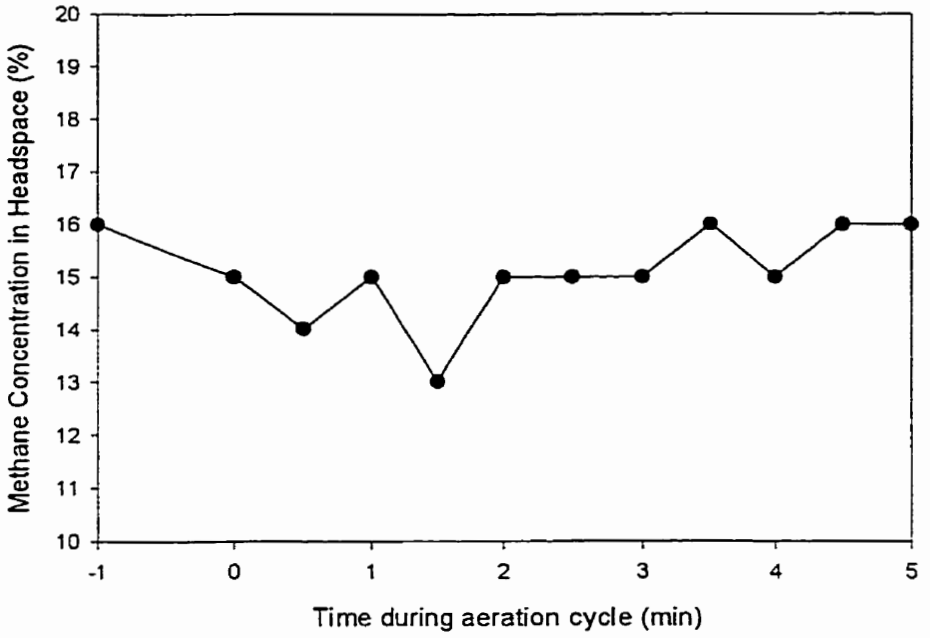

Figure 7.10: Methane concentration of 28%a soil biocell on day 10 of experimental run during aeration cycle; includes measurement one minute prior to aeration

The results of the relative heat generation analysis and volatile solids destruction support the headspace analysis results. The drop in relative heat generation corresponds to the presence of methane in biocells above 26% soil. Once the biocell becomes anaerobic, the destruction of the volatile solids within the biocell is slower. This causes the microbial community to produce less heat than would occur within an aerobic setting, seen as a significant drop in the relative heat generation that occurs at approximately 26% contaminated soil loading, where anaerobic conditions were confirmed by headspace analysis. The drop in volatile solids reduction beyond 24% soil loading indicates that the

microbial community has more difficulty degrading the biodegradable fraction of the compost mixture, which could be due to the decreased oxygen levels apparent at this soil loading. The oxygen levels have impeded the aerobic microorganisms degradative efforts, as supported by the results of Hupe et al. (1998). Beyond the 26% soil loading, this drop in the volatile solids reduction was due to the anaerobic conditions, as anaerobic destruction is typically slower than aerobic destruction.

7.3.4 Free Air Space (FAS) Profiles and Oxygen Transfer

Initial FAS measurements were performed before the beginning of each experimental run. Over the experimental run, the decrease in FAS was monitored through the decrease in height of the biocell. The height decrease was used to calculate the final FAS of each soil loading compost mixture.

7.3.4.1 Initial FAS Results

The initial FAS of each soil loading is shown in Figure 7.11, with the raw results summarized in Appendix C. Initial FAS results ranged from 34% to 43%, with a slight decreasing trend as soil loading increased. According to the initial FAS results, at the highest soil loading rate, 30% soil by wet weight, the initial FAS of the compost was 34.22%, which is adequate for composting. Initial FAS measurements for all soil loadings indicate that adequate FAS exists for composting at the start of the experimental run. A decreasing trend to the initial FAS data is shown using a linear regression fit to the data, with an r^2 value of 0.68.

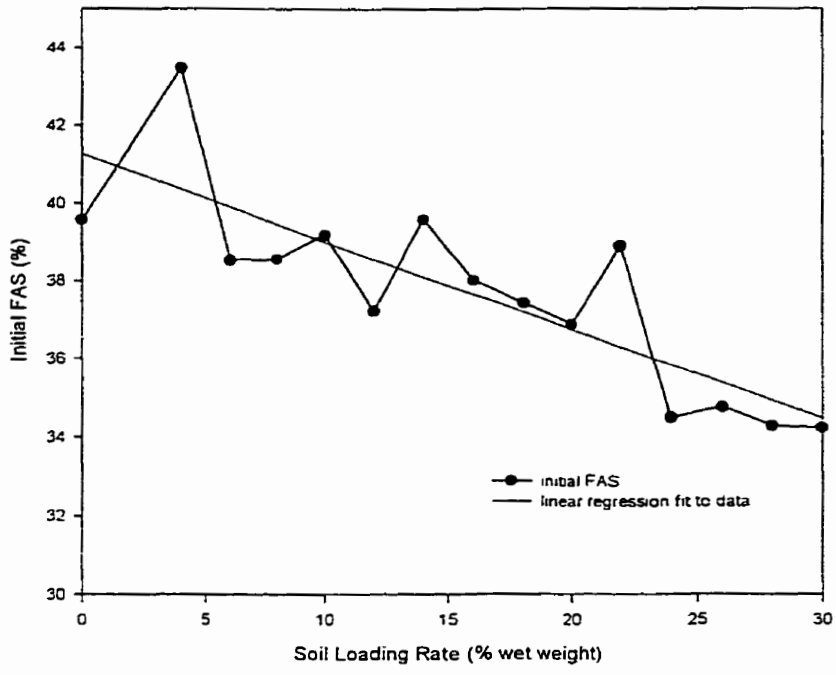

Figure 7.11: Effect of soil loading on initial FAS

7.3.4.2 Height Decrease in Biocells

The biocell height measurements are presented in raw form in Appendix C-3. The height decrease observed during this study was distributed over the experimental run of two weeks, as shown in Figure 7.12. The loading applied during this study resulted in a gradual reduction in biocell height. The results from Chen (1998), using a loading of 39.4 N. compared to the 22 N used during this study, followed a significantly different pattern. Chen (1998) found that the FAS reduction was 60% of the total reduction after one minute of loading, and that 90% of the total reduction was reached after one hour. The lower loading, as well as the addition of clay soil, appear to have affected the settlement pattern. The clay

soil may provide a less compressible element in the compost, affecting FAS decreases over the experimental run.

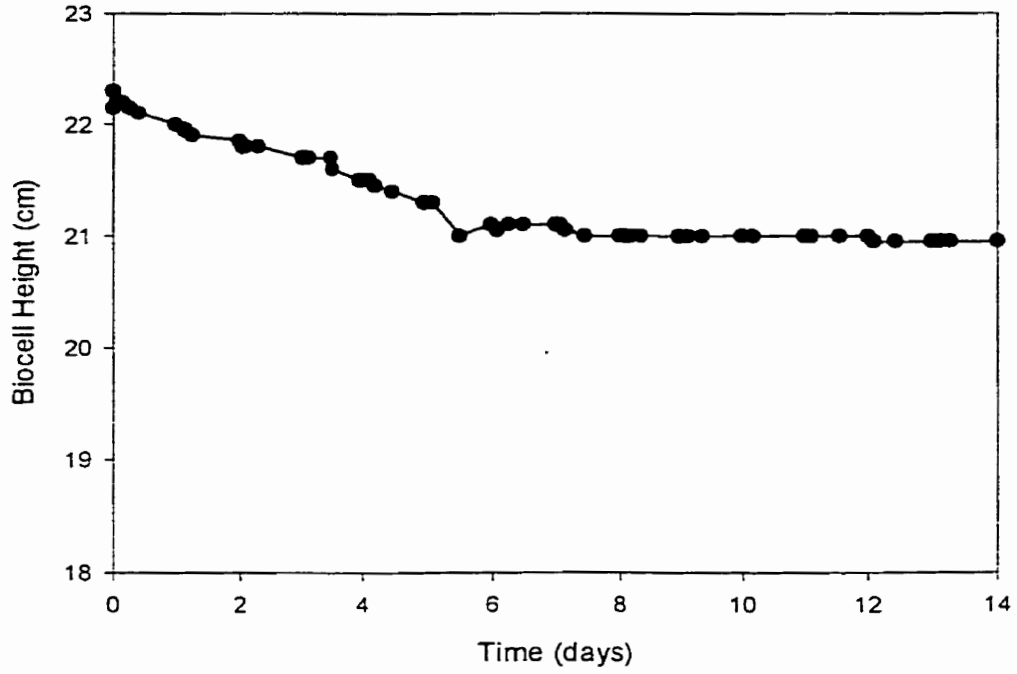

Figure 7.12: Typical biocell height decrease over experimental run

7.3.4.3 FINAL FAS

The results for the final FAS calculations are found in Appendix C-1. The biocells were compared using the relationship of the ratio of the final FAS to the initial FAS, as shown in Figure 7.13. This relationship was used to demonstrate the amount of compression as it related to the initial free air space.

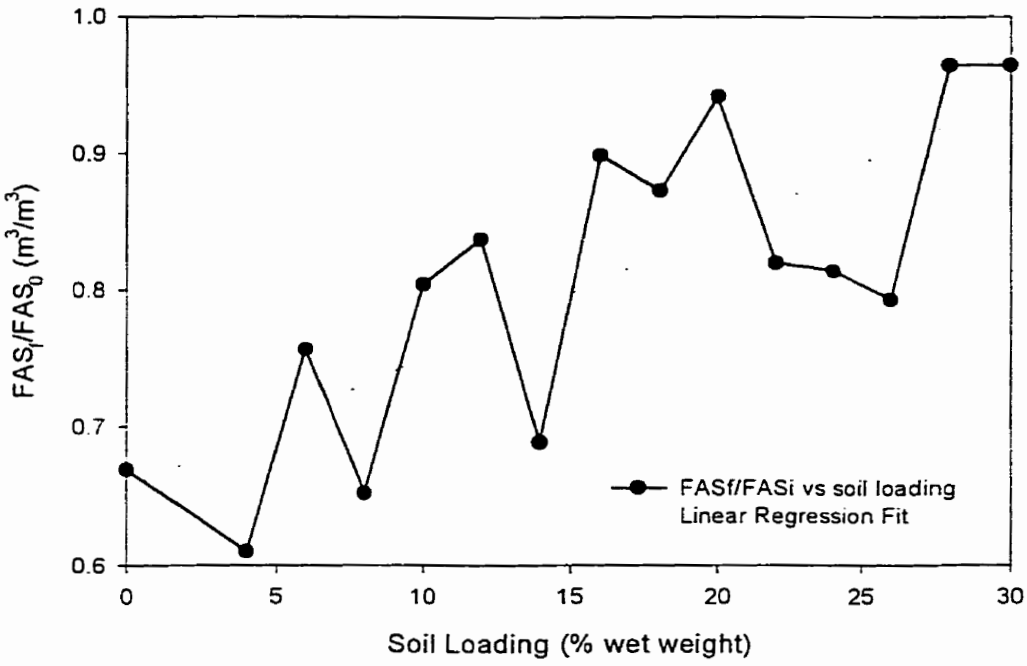

Figure 7.13: Effect of soil loading on ratio of final FAS to initial FAS, with linear regression line of best fit indicated

As seen in Figure 7.13, the data are scattered. However, an increasing trend is seen with increasing soil loading as indicated by the linear regression fit to the data ($r^2 = 0.59$). As more clay soil is added to the compost, the compressibility of the compost mixture decreases. This may be due to the clay particles (nuggets) adding strength to the co-compost mixture. The FAS of the biocell can also be affected by the spatial distribution of the clay particles within the compost biocell. An even distribution would provide ideal FAS settling, but a homogeneous compost mixture is extremely difficult to create. If the clay nuggets are located in a region of the biocell and are compressed together over the experimental run, they

may effectively block the air flow through areas of the biocell and cause anaerobic conditions to occur within the biocell. The 28% and 30% contaminated soil biocells may be evidence of this phenomenon, where the clay within the biocells prevents oxygen transfer within the biocells, causing the anaerobic conditions observed within the biocells.

7.3.5 TPH DATA RESULTS

Initial results of TPH testing, performed on the woodchips, showed that the TPH testing detected the background TPH in the compost components in levels significantly above the diesel contamination proposed for the experiment. The results of the initial TPH testing are presented in Appendix C-6, and are summarized in Table 7.6.

Table 7.6: Mean Initial TPH Testing Results for Woodchips

	TPH mg kg^{-1} (wet basis)	Percent Relative Standard Deviation (%)
C_{10}	251.93	3.8
C_{11}	167.86	4.2
C_{12}	93.23	4.7
C_{13}	321.99	8.4
C_{14}	1031.58	5.0
C_{15}	632.10	1.6
C_{16}	569.12	2.7
C_{17}	146.36	2.3
C_{18}	151.73	2.3
C_{19}	9993.5	0.8
Total:	13359.41	

Levels of TPH in the woodchips alone were greater than the 5000 mg kg^{-1} dry soil of diesel contamination. An attempt was made to dry the chips to remove the volatile compounds, as it was thought that some of the more volatile hydrocarbons could be removed through drying. As shown in Table 7.7, drying the woodchips removed some of the TPH compounds, but some of the higher end compounds remained in the woodchips in substantial concentrations. Also, drying the woodchips will necessitate the addition of water to the compost mixture to obtain an adequate moisture content. The addition of water is undesirable at the field scale.

Table 7.7: Mean TPH results on dried woodchips

	TPH mg kg^{-1}	Percent Relative Standard Deviation (%)
C_{10}	18.18	10.1
C_{11}	3.07	4.5
C_{12}	0	0
C_{13}	62.12	1.6
C_{14}	374.89	1.3
C_{15}	217.92	0.9
C_{16}	119.75	2.7
C_{17}	14.05	10.9
C_{18}	49.09	5.6
C_{19}	2310.17	0.6
Total:	3169.23	

The TPH method used was also unable to quantify the amount of diesel fuel remaining in the clay soil at the end of each experimental run. This was due to several

factors. The first factor was the design of the method, which involved extraction of diesel fuel from pure clay soil. Upon completion of composting, it was not possible to separate the clay soil from the biosolids/woodchips compost mixture. The experimental method then requires the extraction of the TPH compounds from the biosolids, woodchips and soil mixture, causing difficulty in obtaining a representative sample. It is also difficult to determine the amount of anhydrous material to add to the sample prior to extraction for analysis, since woodchips do not require the addition of anhydrous material prior to analysis, unlike the biosolids and clay soil. Due to this difficulty, TPH concentrations were not measured at the termination of the experimental run. Another factor that affected the utilization of TPH testing was the level of TPH compounds in the woodchips, present in levels substantially exceeding the TPH levels of 5000 mg kg^{-1} dry soil in the clay soil, and therefore masking the contribution of diesel fuel to the total TPH concentrations. The measurement of final TPH concentrations, if feasible, may possibly have aided in determining hydrocarbon usage through examination of comparative peaks in diesel and woodchips respectively.

7.3.6 $^{14}CO_2$ DATA RESULTS

The $^{14}CO_2$ generation of the biocells was determined through the volatile traps of NaOH through which the offgases from the biocells were bubbled. The traps were sampled in triplicate and analysed using the Beckman LS 7000 Scintillation Counter in the Soil Science Department at the University of Manitoba. The results of the testing indicate that levels of radioactivity in the offgas of the biocell were negligible; the analysis indicated that

the traps measured extremely close to the levels of background radiation present. The results of the $^{14}CO_2$ testing are presented in Appendix C, with the average $^{14}CO_2$ recoveries for each soil loading presented in Table 7.8:

Table 7.8: Total $^{14}CO_2$ recovery over experimental run for all biocells

Soil Loading (% wet weight)	Total $^{14}CO_2$ recovery over experimental run (%)
0	0
4	0.0004
6	0.0002
8	0.002
10	0.0003
12	0.00006
14	0.00004
16	0.0002
18	0.00009
20	0.0008
22	0.000004
24	0.00001
26	0.0002
28a	0.0001
28b	0.000004
30a	0.000005
30b	0

There are three possible explanations for this phenomenon. The first is that the traps did not function to trap the $^{14}CO_2$ and were therefore not an accurate representation of the

$^{14}CO_2$ generation over the experimental run. This explanation was refuted through weighing the NaOH traps before and after the experimental run; an increase in weight was observed, indicating that the traps were functioning. Also, as a second check for the traps, a co-compost mixture was prepared, diesel fuel was added to make 20,000 mg diesel kg^{-1} wet co-compost. This mixture was placed in a biocell, and was put in the environmental chamber at 45 °C for fourteen days. The trap was then monitored for ^{14}C after the fourteen days had elapsed; the presence of ^{14}C in levels above background indicated that the traps were functioning to trap respired $^{14}CO_2$. The second possible explanation for the lack of respired $^{14}CO_2$ observed over the experiment is that the radio-labelled octadecane was not utilized by the microorganisms. This is possible, since the biocells were allowed to run for a maximum of 14 days, during which microorganisms had to acclimate themselves. The diesel is also tightly bound to the clay soil and may prove to be difficult to degrade in a short time. The work of Man (1998) indicated that for clay soil incubated at 22°C, $^{14}CO_2$ was recovered beginning on day 14 of his experimental run, at approximately 4% of the total ^{14}C added. Significant recoveries occured over the experimental run, with a final percent recovery as $^{14}CO_2$ of approximately 45%, over a span of 210 days. A longer cocomposting time will likely produce substantial $^{14}CO_2$ recovery. The third explanation is that the co-composting environment also may promote the formation of bound residues, supported by the work of Kästner et al. (1995), who observed $^{14}CO_2$ generation using 1-^{14}C-hexadecane in sandy soil composting in minimal amounts during the first 12 days of co-composting, and observed a lack of $^{14}CO_2$ production from 9-^{14}C-anthracene during the first 12 days of co-composting. The work of Kirchmann and Ewnetu (1998) on co-composting of oil wastes in horse manure

also observed little carbon mineralization during the first 10 days of composting. An aerobic/anaerobic system utilizing [^{14}C] TNT degradation showed that about 84% of the radioactivity was bound to the humic compounds and did not measure any generation of $^{14}CO_2$ (Drzyga et al., in Bruns Nagel et al., 1998). The work of Diaz at al (1995) showed that hydrocarbon utilization occurred within the first 13 days of composting. However, Diaz et al. (1995) used oily wastes and did not use contaminated soil; the pure oily waste material is more readily available for degradation than wastes sorbed to clay soils. The ^{14}C content of the cocompost mixture at the end of the experimental run was not determined; this was due to difficulties with the extraction procedure for hydrocarbons, as described for the total petroleum hydrocarbon analysis in the previous section.

8.0 SUMMARY AND CONCLUSIONS

The objective of this thesis was to determine the maximum soil loading rate for diesel contaminated heavy clay soil added to a woodchips-biosolids co-compost mixture. The maximum soil loading rate was determined through analysis of microbial activity, measured as relative heat generation, volatile solids destruction, and headspace gas composition. The change in free air space of the compost was also measured over the experiment, as was the respiration of $^{14}CO_2$ from a radiolabelled compound added to the diesel fuel. An attempt to monitor the degradation of TPH compounds was made.

The first step of the experiment was to determine the compost mixture recipe. In order to do this, an initial characterization of the compost amendments, the woodchips and biosolids, was performed. The amendments were characterized for organic carbon, total Kjeldahl nitrogen, moisture content, and volatile solids content. In order to determine whether the soil used for the experiment had been previously contaminated by hydrocarbons, the soil was characterized for total volatile hydrocarbons ($>C_{10}$), total semi-volatile hydrocarbons (C_{10} to C_{30}), and heavy extractable hydrocarbons ($>C_{30}$). The soil was also characterized for carbon content, nitrogen, metals content and grain size distribution. After characterization had been completed, the compost recipe was created, using a target moisture content of 55%.

The loading to be applied during the experimental run was determined through empirical testing. A mid-range compost mixture was prepared and placed into biocells. Using the density of the compost, and assuming a compost heap height of 1.22 m, the

theoretical loading was calculated and then applied to the biocells and allowed to act for one hour. The compression of the compost was measured after one hour, and used to calculate a new bulk density of the compost. Using this new bulk density, the new loading for the biocells was calculated, applied, and allowed to act. These steps were repeated until the loading applied was within 1% of the calculated loading. Initial FAS was also determined for each soil loading compost mixture.

With the compost recipe, initial FAS and the biocell loading calculated, the next step of the study consisted of creating the compost mixtures for the biocells, and using the biocells to simulate composting over a period of two weeks. The biocells were constructed to allow a supply of gas (in this case air), which was supplied through pumps connected to a programmable controller. Air was supplied for 5 minutes of every hour during the two week experimental run. The biocells were also equipped with a septum for headspace sampling, which was performed during days 0, 5 and 10 of the experimental run for oxygen and methane levels in the headspace. The offgas from each biocell was collected with tubing and bubbled through flasks containing NaOH to trap respired CO_2.

A total of seventeen biocells were run for a two week span; soil loadings ranged from 0% to 30% soil loading. One biocell contained 0% soil; one biocell was used for each soil loading from 4% to 26% (in increments of 2%); duplicates were performed for 28% and 30% contaminated soil biocells, in order to confirm the anaerobic conditions encountered in these biocells. Biocells were loaded with the compost mixture, to which clay soil contaminated with 5000 mg kg^{-1} dry clay soil of diesel fuel spiked with 1-^{14}C-octadecane was added. Biocells were placed in an environmental chamber, which was initially set at 35 °C, then

ramped 2 °C each day until reaching 45 °C, where the chamber temperature remained for the remainder of the two weeks. This program was chosen to mimic the temperature of a compost heap surrounding each biocell. During the two weeks, each biocell was loaded with the empirically determined loading and monitored at least three times daily for temperature and biocell height. Biocell temperature monitoring results were used to calculate the relative heat generation of each soil loading, through determination of degree-days above 35 °C for each soil loading biocell. Volatile solids destruction analysis was performed on the compost after each experimental run. The decrease in FAS over the compost run was monitored through the biocell height decrease. Samples of woodchips were analysed for TPH content, and samples were taken from the NaOH traps and analyzed for ^{14}C, to indicate the respiration of $^{14}CO_2$.

Results indicate that above 20% contaminated soil, oxygen levels begin to decrease until above 26% soil, where anaerobic conditions were encountered in headspace testing. The anaerobic conditions were supported by the volatile solids and relative heat generation results, which indicated that above 26% soil the relative heat generation and volatile solids destruction decreased sharply.

Free air space results indicate that the addition of clay soil appears to affect the compressibility of the compost mixture; at higher soil loadings the ratio of final FAS to initial FAS was close to 1.0; at lower soil loadings the ratio was in the range of 0.74 to 0.76.

The results of the TPH analysis performed on the woodchips indicated that the concentrations of naturally occuring TPH compounds within the woodchips were high enough to mask the diesel present in the biocells. The woodchips were dried and reanalysed

to determine if this process would reduce the TPH results to acceptable levels; after drying, TPH concentrations were still present in enough concentration to mask diesel fuel or affect results. For this reason, TPH analysis was not performed on the compost mixture.

The $^{14}CO_2$ results showed that no respired $^{14}CO_2$ was trapped within the NaOH mixture. These results indicate that the active composting phase is not sufficient to degrade diesel fuel compounds from clay soils.

From the results obtained, the following conclusions were made:

1. The recommended maximum soil loading for co-composting of heavy clay soil is less than 20%, in order to maintain maximum oxygen levels and prevent anaerobic conditions from occuring.
2. A method for determining TPH compounds in diesel fuel separately from naturally occuring hydrocarbons in the woodchips and biosolids needs to be developed for use in the Environmental Engineering Laboratory at the University of Manitoba. The method would allow for determination of degradation, transformation, or binding of diesel compounds during co-composting.
3. The active co-composting phase is not sufficient to degrade diesel compounds sorbed to heavy clay soils. A longer composting time may allow for degradation of diesel fuels from the soils.
4. A protocol for measuring initial FAS for heavily organic substances such as compost mixtures would provide more consistent results and allow for comparability between researchers.

9.0 SUGGESTIONS FOR FURTHER STUDY

Several suggestions for further study have evolved from the work performed during this experimental study. The volatile solids analyses seem to have inherent variabilities due to the non-homogeneous compost mixtures used in this experiment. I believe that these values are to be expected when working with such a non-homogeneous substance. The analysis is more accurate than previous analyses due to the present technique of grinding the compost before analysis. However, the grinding does not completely remove the variability in analysis, which must be expected when working with highly variable organic substances.

There is an inherent difficulty in obtaining representative samples, as well as ensuring that clay soil is distributed evenly throughout the compost; clay soil also poses a difficulty since it will form "nuggets" as well as coating the woodchips, and does not do so in consistent patterns.

There is a need for a TPH analysis that does not include hydrocarbons from the compost materials. Methods do exist for this purpose; however they need to be developed for use in the Environmental Engineering laboratory. The analysis should be simple enough to be performed by students in the Environmental Engineering laboratory facilities at the University of Manitoba to render the method applicable. A potential solution may be to compost the woodchips and biosolids mixture before the addition of soil; allowing microorganisms to degrade the naturally occuring hydrocarbons present in the woodchips and biosolids may reduce these concentrations to negligible levels, allowing for diesel addition as the sole source of hydrocarbons in the co-compost mixture.

The FAS method needs to modified for organic substances such as compost. This would provide more confidence when comparing results between researchers. The current method provides results that are dependent on the compaction of the compost mixture that the researcher creates, which vary from researcher to researcher, as well as varying between trials for a researcher.

Realtime monitoring of headspace, height reduction and temperature would provide more exact results and provide more meaningful conclusions. Determining at which point during pre-aeration the compost headspace begins to show anaerobic conditions would be of interest, and realtime temperature monitoring would provide more accurate relative heat generation calculations.

An examination of the effect of the thermal regime (environmental chamber temperatures) would be beneficial for explaining the presence or absence of spikes in the biocell temperature profiles.

The experiment should be replicated, likely within a Ph.D. program or Master's program to ensure that the results obtained are accurate and repeatable, and to help define the maximum soil loading with accuracy.

REFERENCES

Al-Daher R., Al-Awadhi N., El-Nawawy A. 1998. "Bioremediation of Damaged Desert Environment Using the Windrow Soil Pile System in Kuwait". Environment International. 24 (1/2), p. 175-180.

Alexander, M. 1999. Biodegradation and Bioremediation. 2nd edition. Academic Press. San Diego.

APHA. 1991. Standard Methods for the examination of Water and Wastewater. American Public Health Association, American Water Association, Water Environment Federation, 19th Edition.

Atlas R.M., Bartha R. 1997. Microbial Ecology: Fundamentals and Applications. Benjamin/Cummings Science Publishing. Menlo Park CA. 4th edition.

Baracos A. 1977. "Compositional and Structural Anisotropy of Winnipeg Soils - a study based on scanning electron microscopy and X-ray diffraction analyses". Canadian Geotechnical Journal. 14 (1), 125-137.

Baracos A., Graham J. 1980. "Landslide problems in Winnipeg". Specialty Conference on Slope Stability Problems in Urban Areas. Canadian Geotechnical Society. Toronto.

Baracos A., Graham J., Domaschuk L. 1979. "Yielding and Rupture in a Lacustrine Clay". 32nd Canadian Geotechnical Conference. Quebec.

Beaudin, N., Caron, R.F., Legros, R., Ramsay, J., Lawlor, L., Ramsay, B. 1996. Co-composting of Weathered Hydrocarbon Contaminated Soil. Compost Science and Utilization, Vol 4, No. 2, 37-45.

Benoit, P., Barriuso, E. 1995. "Effect of Straw Composting on the Degradation and Stabilization of Chlorophenols in Soil", Compost Science and Utilization, 3: 31-37.

Berg M.S., Loehr R.C., Webster M.T. 1998. "Release of Petroleum Hydrocarbons From Bioremediated Soils". Journal of Soil Contamination. 7 (6), 675-695.

Block R.N., Allworth N., Bishop M. 1991. "Assessment of Diesel Contamination in Soil" in Hydrocarbon Contaminated Soils Volume I. Calabrese E.J. and Kostecki P.T., eds. Lewis Publishers. Chelsea, Michigan.

Bruns-Nagel D., Drzyzga O., Steinbach K., Schmidt T.C., Von Löw E., Gorontzy T., Blotevogel K.-H., Gemsa D. 1998. "Anaerobic/aerobic composting of 2,4,6-Trinitrotoluene-Contaminated Soil in a Reactor System". Environmental Science and Technology. 32 (11), 1676-1679.

Burton, Dr. D. 1997. Course Notes, "40.450 Remediation of Contaminated Land" University of Manitoba.

Carter, M.R. 1993. Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, Fl. U.S.A.

Chen, Hongtu. 1998 "The Influence of Compaction and Amendment Type on Biological Activity During Biosolids Co-Composting". Master of Science Thesis, University of Manitoba.

Cho, B-H., Chino, H., Tsuji, H., Kunito, T., Makishima, H., Uchida, H., Matsumoto, S., Oyaizu, H. 1997a. "Analysis of Oil Components and Hydrocarbon-Utilizing Hicroorganisms During Laboratory-Scale Bioremediation of Oil-Contaminated Soil of Kuwait". Chemosphere. 35 (7), 1613-1621.

Cho, B-H., Chino, H., Tsuji, H., Kunito, T., Nagaoka, H., Otsuka, S., Yamashita, K., Matsumoto, S., Oyaizu, H. 1997b. "Laboratory-Scale Bioremediation of Oil-Contaminated Soil of Kuwait with Soil Amendment Materials". Chemosphere. 35 (7), 1599-1611.

Coleman D.C., Fry B. 1991. Carbon Isotope Techniques. Academic Press Inc. San Diego California.

Cookson, J.T. Jr. 1995. Bioremediation Engineering: Design and Application. McGraw-Hill Inc. New York.

Craig, R.F. 1992. Soil Mechanics. 5th edition. Chapman and Hall. London.

Diaz, L.F., Savage, G.M., Golueke, C.G. 1995. "Stabilization of Hazardous Wastes Through Biotreatment". In The Science of Composting, Part 1. Blackie Academic and Profesional.

DOD Environmental Technology Transfer Committee. 1994. Remediation Technologies Screening Matrix and Reference Guide. Second Edition. October 1994.

Domenico P.A., Schwartz F.W. 1990. Physical and Chemical Hydrogeology. John Wiley and Sons. Toronto.

Douglas G.S., McCarthy K.J., Dahlen D.T., Seaver J.A., Steinhauer W.G., Prince R.C., Elmendorf D.L. 1992. "The Use of Hydrocarbon Analyses for Environmental Assessment and Remediation". In Contaminated Soils, Diesel Fuel Contamination. Editors Kostecki P.T., Calabrese E.J. Lewis Publishers Inc. Michigan.

Dragun J. 1988. The Soil Chemistry of Hazardous Materials. Hazardous Materials Control Institute,. Greenbelt, Maryland.

Dragun J., Mason S., Barkach J. 1991a. "What do we Really Know about the fate of diesel fuel in Soil Systems?" in Hydrocarbon Contaminated Soils. Eds. Kostecki P.T., Calabrese E.J. Lewis Publishers.

Dupont R.R., Doucette W.J., Hinchee R.E. 1991. Assessment of in situ bioremediation potential and the application of bioventing at a fuel-contaminated site. in In Situ Bioremediation. Butterworth-Heinemann, Stoncham, MA. pp. 262-281.

Environmental Engineering Department Diesel Fuel in Soil Method (1996)

Gabarini, D.R., Lion, L.W. 1986. "Influence of the Nature of Soil Organics on the Sorption of Toluene and Trichloroethylene". Environmental Science and Technology. 20, 1263-1269.

Guideline 96-05. Treatment and Disposal of Petroleum Contaminated Sites. June 1996. Revised May 1998. Manitoba Environment.

Haug, R.T. 1993. The Practical Handbook of Compost Engineering. Lewis Publishers. Ann Arbor.

Henner P., Schiavon M., Morel J.L., Lichtfouse É. 1997. "Polycyclic aromatic hydrocarbon (PAH) occurrence and remediation methods". Analusis. 25 (9-10), M56-M59.

Hupe, K. Lüth, J.-C. Heerenklage, J. Stegmann, R. 1996. "Enhancement of the Biological Degradation of Soils Contaminated with Oil by the Addition of Compost". Acta Biotechnologica. 16 (1), 19-30.

Joyce J.F., Sato C., Cardenas R., Surampali R. 1998. "Composting of Polycyclic Aromatic Hydrocarbons in Simulated Municipal Solid Waste". Water Environment Research. 70 (3), 356-361.

Kästner M., Lotter S., Heerenklage J., Breuer-Jammali M., Stegmann R., Mahro B. 1995. "Fate of ^{14}C-labeled anthracene and hexadecane in compost-manured soil". Applied Microbiology and Biotechnology. 43, 1128-1135.

Kirchmann, H. Ewnetu, W. 1998. "Biodegradation of petroleum-based oil wastes through composting". Biodegradation. 9, 151-156.

Kjartanson B. 1983. Geological Engineering Report for Urban Development of Winnipeg. Department of Geological Engineering. University of Manitoba. Winnipeg. eds. Baracos A., Shields D.H., Kjartanson B.

Klein C., Hurlbut C.S. Jr. 1993. Manual of Mineralogy. 21st edition. John Wiley and Sons Inc. Toronto.

Klute A. et al. 1986. Methods of Soil Analysis. American Society of Agronomy Inc., Soil Science Society of America Inc., Madison Wisconsin, U.S.A.

Laine, M.M., Ahtiainen, J., Wågman, N., Öberg, L.G., Jørgensen, K.S. 1997. "Fate and Toxicity of Chlorophenols, Polychlorinated Dibenzo-*p*-dioxins, and Dibenzofurans during Composting of Contaminated Sawmill Soil". Environmental Science and Technology. 31 (11), 3244-3250.

Laine M.M., Jørgensen K.S. 1997. "Effective and Safe Composting of Chlorophenol-Contaminated Soil in Pilot Scale". Environmental Science and Technology. 31 (2), 371-378.

Larsen, K. 1998. The Effect of C:N Ratio on Bench-Scale Composting of Pulp and Paper Biosolids. Master of Science Thesis, University of Manitoba.

Lilja L.T., Uotila-Juve, J., Silvennoinen, H. 1995. "Bioremediation of PAH- Contaminated Soil" In The Science of Composting. Blackie Academic and Professional.

Liu, X., Cole, M.A., 1995. "Minimum Effective Compost Addition for Remediation of Pesticide-Contaminated Soil" In The Science of Composting. Blackie Academic and Professional.

Loh, A.H., Holt, R.T. 1974. "Directional varation in undrined shear strength and fabric of Winnipeg upper brown clay". Canadian Geotechnical Journal. 11, 430-437.

Man, Alex. 1998. "Temperature Effect on Bioremediation Kinetics of Diesel Fuel Contaminated Winnipeg Clay". Master of Science Thesis, University of Manitoba.

McGill W.B., Rowell M.J., Westlake D.W.S. 1981. "Biochemistry, Ecology and Microbiology of Petroleum Compounds in Soil". in Soil Biochemistry. Volume 5. Ed. E.A. Paul. Marcel Dekker Inc. New York, New York.

McMurry, J. 1992. Organic Chemistry. 3rd edition. Brooks/Cole Publishing Company. Pacific Grove, CA.

Millner, G.C., James, R.C., Nye, A.C. 1992. "Human Health-Based Soil Cleanup Guidelines for Diesel Fuel No. 2". Journal of Soil Contamination, 1(2), 103-157.

Munson B.R., Young, D.F., Okiishi T.H. 1994. Fundamentals of Fluid Mechanics. John Wiley and Sons, Inc. Toronto

NCHRP (National Cooperative Highway Research Program). 1997. NCHRP Synthesis 226: Remediation of Petroleum-Contaminated Soils: A Synthesis of Highway Practice. Transportation Research Board, National Research Council. National Academy Press. Washington DC.

NRAES (Northeast Regional Agricultural Engineering Service). June 1992. On Farm Composting Handbook.

Nyer E.K. 1993. Practical Techniques for Groundwater and Soil Remediation. Lewis Publishers, Ann Arbor.

Render F.W. 1970. Geohydrology of the Winnipeg area as related to groundwater supply and construction. Manitoba Mines Branch Geological Paper, National Research Council of Canada, Ottawa.

Ribbons D.W., Eaton R.W. 1982. "Chemical Transformations of Aromatic Hydrocarbons that Support the Growth of Microorganisms". in Biodegradation and Detoxification of Environmental Pollutants. Ed. A.M. Chakrabarty. CRC Press Inc. Boca Raton, Florida.

Riser-Roberts, E. 1992. Bioremediation of petroleum contaminated sites. CK Smoley. CRC Press Inc., Boca Raton.

Tchobanoglous G., Thiesen H., Vigil S. 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill Inc. Toronto.

Teller J.T. 1985. Glacial Lake Agassiz and its influence on the Great Lakes. Quaternary Evolution of the Great Lakes: Geological Association of Canada Special Paper 30. pp. 1-16.

Valo R., Salkinoja-Salonen, M. 1986. "Bioreclamation of chlorophenol-contaminated soil by composting" Applied Microbiol Biotechnol 25: 68-75.

Wang C.H., Willis D.L., Loveland W.D. 1975. Radiotracer Methodology in the Biological, Environmental, and Physical Sciences. McElroy W.D., Swanson C.P. Eds. Prentice-Hall Toronto.

Williams, R.T., Keehan, K.R., 1993. "Hazardous and Industrial Waste Composting". Science and Engineering of Composting, Ohio State University.

Wischmann, H., Steinhart, H. 1997. "The Formation of PAH Oxidation Products in Soils and Soil/Compost Mixtures". Chemosphere. 35 (8), 1681-1698.

Zeigenfuss, P.S., Williams, R.T., Myler C.A. 1991. "Hazardous Materials Composting". Journal of Hazardous Materials, 28, 91-99.

APPENDIX A:
EXPERIMENTAL PHASE I RESULTS

APPENDIX A-1
CHARACTERIZATION RESULTS FOR BIOSOLIDS

Biosolids Analysis

Moisture Content Data

Crucible #	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture (wet basis)	%TS (wet basis)	%VS (dry basis)	%ash (dry basis)	%OC (dry basis)
43	83.7553	93.7202	86.9092	85.6659	6.811	68.349908	31.650092	39.421034	60.578966	21.900575
47	84.0855	106.532	91.1503	88.4454	15.3817	68.526051	31.473949	38.287	61.713	21.270556
30	94.149	104.3237	97.3742	96.1306	6.9495	68.301768	31.698232	38.558849	61.441151	21.421583
23	90.5373	109.1294	96.382	94.1545	12.7474	68.56353	31.43647	38.111451	61.888549	21.173029
25	92.1495	109.2254	97.5193	95.4569	11.7061	68.553341	31.446659	38.407389	61.592611	21.337439
45	83.1756	105.7459	90.1622	87.4397	15.5837	69.045161	30.954839	38.967452	61.032548	21.648584
mean						68.556627	31.443373	38.625529	61.374471	21.458627
Std Dev						0.240605	0.240605	0.443593	0.443593	0.2464406

TKN Analysis Data

Water Blanks:		Charted Value
	1	5.45
	2	4.9
	3	5.24
	4	5.35
	mean	5.235
	std dev	0.207183

Standards	Charted Value:
1.0 mg/L	10.6
1.0 mg/L	10.1
5.0 mg/L	15.4
5.0 mg/L	15.25
10 mg/L	26
10 mg/L	25.2

Biosolids:		Weight	Chart	N (mg/L)	N (mg/kg)	%N
	1	0.1 g	19.1	6.42	32100	3.21
	2	0.1 g	18	5.97	29850	2.985
	3	0.1 g	18.5	6.24	31200	3.12
					mean:	3.105
					Std Dev:	0.0924662

Density: volume: (cm^3)	weight: (g)	wet bulk density: (g/cm^3)
200	233.51	1.16755

Results: %N	%OC	C:N	wb density (kg/m^3)
3.105	21.45863	6.9	1167.55

APPENDIX A-2
CHARACTERIZATION RESULTS FOR WOODCHIPS

Woodchips Analysis **woodchips dried prior to TKN analysis

Moisture Content Data

Crucible #	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moistur (wet basis	%TS (wet basis	%VS (dry basis	%ash (dry basis	%OC (dry basis)
J11	91.5854	95.048	93.6478	92.2253	1.4002	40.43782	59.56218	68.97304	31.02696	38.31836
56	96.8029	102.5234	100.0318	98.0048	2.4916	43.55563	56.44437	62.7768	37.2232	34.876
72	80.9629	83.427	82.3913	81.4373	1.0357	42.03157	57.96843	66.78801	33.21199	37.10445
81	103.9017	109.0309	107.1025	104.83	1.9284	37.59651	62.40349	70.99788	29.00212	39.44326
J4	90.9252	94.1858	92.7843	91.4565	1.4015	42.98289	57.01711	71.42166	28.57834	39.6787
mean						41.32088	58.67912	68.19148	31.80852	37.88415
Std Dev						2.140665	2.140665	3.168887	3.168887	1.760493

TKN Analysis Data

Water Blanks:		Charted Value	Standards Charted Value:	
1		8.5	1.0 mg/L	13
2		8.25	1.0 mg/L	12.75
3		8.5	5.0 mg/L	20
4		9.25	5.0 mg/L	19.75
	mean	8.625	10 mg/L	29.25
	std dev	0.375	10 mg/L	28

Biosolids:		Weight	Chart	N (mg/L)	N (mg/kg)	%N (db)
	1	0.1 g	25.5	8.2	4100	0.41
	2	0.1 g	21.5	6.2	3100	0.31
	3	0.1 g	27	8.98	4490	0.449
					mean:	0.389667
					Std Dev:	0.05854

Density: volume: (cm^3)	weight: (g)	wet bulk density: (g/cm^3)
200	20.59	0.10295

Results:	%N	%OC	C:N	wb density (kg/m^3)
	0.389667	37.88415	97.22195	102.95

APPENDIX A-3
COMPOST RECIPE RESULTS

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)	68.56	3.11	6.9	1167.55
Dry (a)	41.32	0.4	97.21	102.95

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 =	55	%
The required amount of amendment =	0.991	kg per kg of material b.
The resulting C:N Ratio =	24.26	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 =	3366	tonnes / year
Enter the amount of volume reduction expected (default = 0.8) =	0.8	
The resulting volume of mixture at start-up is =	28233	cubic metres per year
The resulting weight of material at start-up is =	6702	tonnes / year
The resulting bulk density at start-up is =	237	kg / cubic metre

To determine the volume of material on the composting pad:

a. Enter the material retention time (MRT) for the compcsting 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 =	30	days
Enter the shrinkage factor =	0.75	
The resulting material volume of the composting pad is =	1740.41	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 ft) to 3.6 m (12 ft).
c. Record the length, height, base width, & the required number of windrows.

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Enter the windrow length =	50	metres
Enter the target pile height =	1.8	metres
The resulting pile base width is =	3.00	metres
The resulting number of windrows are =	9.7	windrows

To determine the composting area requirements:

a. Enter the space required between each windrow. Typically, 6 metres (20 feet) are required between each windrow to allow for movement of the bucket loader.

b. Enter the space required between the windrows and the edge of the composting pad. Typically, 3 metres (10 ft) 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 =	90 metres by	56	metres.
The required area for composting is =		5040	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.

f. Record the MRT, the shrinkage factor, theaverage 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	metres		
Enter the space required between the piles and the edge of the pad =	3	metres		
The width of the curing pad as a function of the windrow length =	23.5	metres.		
The amount of material in the curing area is =	1160.3	cubic metres.		
The required pad dimensions are =	47.1	metres by	28	metres.
The required area for curing is =	1320	square metres.		

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 =	6961.6	cubic metres		
The required pad dimensions are =	124.5	metres by	28	metres.

The required area for storage is = 3486 square metres.

To determine the overall pad dimensions:
Sum the requirements for composting, curing, and storage.

The total area required is = 9846 square metres or 2.4 acres.
The total area required per unit weight of wet feedstock = 2.93 square metres per tonne per year.

Design Summary for Print Out.

	MC	N	C:N	Density
Wet Material				
Dry Material				

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APPENDIX B
EXPERIMENTAL PHASE II RESULTS

APPENDIX B-1
LOADING CONDITIONS DATA

Experimental Phase II: Iterative Loading Results

Trial 1 weight of reactor: 1.77 kg
Wt reactor + mix: 2.37 kg
initial volume (cm^3) 2390.76

Iteration	Wet bulk density (kg/m^3)	Stress (Pa)	Calc. Load (N)	Load Used (N)	Calc. Load % difference %	Volume after compaction (cm^3)	Volume reduction (cm^3)	% total volume reduction
1 (initial)	250.97	1967.60	18.02	17.44		2070.16	320.6	13.409962
2	289.83	2272.29	20.81	19.21	13.40865747	2006.04	64.12	16.091954
3	299.10	2344.92	21.48	21.85	3.097345133	1960.24	45.8	18.007663
4	306.08	2399.71	21.98		2.283105023			

% difference between last load used and new calculated load: 0.5973639

Trial 2 weight of reactor: 1.82 kg
Wt reactor + mix: 2.42 kg
initial volume (cm^3) 2381.6

Iteration	Wet bulk density (kg/m^3)	Stress (Pa)	Calc. Load (N)	Load Used (N)	Calc. Load % difference %	Volume after compaction (cm^3)	Volume reduction (cm^3)	% total volume reduction
1 (initial)	251.93	1975.14	18.09	18.04		1987.72	393.88	16.538462
2	301.85	2366.53	21.68	19.16	16.53846154	1960.24	27.48	17.692308
3	306.08	2399.71	21.98	21.92	1.382488479	1951.08	9.16	18.076923
4	307.52	2410.97	22.08		0.46728972			

% difference between last load used and new calculated load: 0.744898

Trial 3 weight of reactor: 1.78 kg
Wt reactor + mix: 2.38 kg
initial volume (cm^3) 2372.44

Iteration	Wet bulk density (kg/m^3)	Stress (Pa)	Calc. Load (N)	Load Used (N)	Calc. Load % difference %	Volume after compaction (cm^3)	Volume reduction (cm^3)	% total volume reduction
1 (initial)	252.90	1982.77	18.16	18.04		2033.52	338.92	14.285714
2	295.05	2313.23	21.19	21.8	14.28571429	1941.92	91.6	18.146718
3	308.97	2422.34	22.19		4.504504505			

% difference between last load used and new calculated load: 1.7517007

Experimental Phase II: Iterative Loading Results

average calc. load:	22.085
stand. dev:	0.085
average % vol red:	18.077
stand. dev:	0.057
average wet bulk density:	307.527
std dev:	1.179

APPENDIX C
EXPERIMENTAL PHASE III RESULTS

APPENDIX C-1
INITIAL FAS DATA

Initial FAS measurements:

PARTICLE DENSITY:

0% soil:

wt flask (g)	wt flask + compost (g)	wt flask+ comp+water (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
136.56	183.97	329.93	336.62	1	24.1	0.88
145.87	201.22	341.87	349.8	1		0.87
128.42	168.7	323.12	328.41	1		0.88
					avg:	0.88
					std dev:	0.00
					% rel std:	0.46

DRY BULK DENSITY:

wt flask (g)	volume flask (cm^3)	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
221.54	100	245.34	232.11	0.1057
256.4	100	281.2	267.06	0.1066
261.81	100	286.01	272.51	0.107
			avg:	0.1064
			std dev:	0.0005
			% rel std:	0.5108

POROSITY:

n = 0.8788

VOLUMETRIC WATER CONTENT:

theta = 0.4831

INITIAL FAS:

FAS = n-theta

FAS = 0.3957

39.57%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heigh	20.6	initial FAS (cm^3)	746.76	Final FAS (% of final volume)	30.46%
final height:	17.9	volume reduction:	247.32	FAS reduction (%)	9.11%
difference:	2.7	Final FAS (cm^3)	499.44		
volume red	247.32				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.66881

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

4% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
137.87	185.85	324.72	337.87	1	24.1	0.78
155.42	203.99	339.48	355.44	1		0.75
139	187.34	323.54	339.01	1		0.76
					avg:	0.77
					std dev:	0.01
					% rel std:	1.85

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried omp+fls (g)	dry bulk density (g/cm^3)
232.15	100	257.02	243.31	0.1116
244.58	100	270.12	256.22	0.1164
220.47	100	244.73	230.83	0.1036
			avg:	0.1105
			std dev:	0.0053
			% rel std:	4.7766

POROSITY:

n = 0.8555

VOLUMETRIC WATER CONTENT:

theta = 0.4208

INITIAL FAS:

FAS = n-theta

FAS = 0.4347

43.47%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	23	initial FAS (cm^3)	915.93	Final FAS (% of final volume)	31.93%
final heigh	19.1	volume reduction:	357.24	FAS reduction (%)	11.54%
difference	3.9	Final FAS (cm^3)	558.69		
volume re	357.24				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.609969

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

6% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
143.15	190.43	334.72	344.01	1		0.84
127.88	165.33	321.51	327.78	1		0.86
139.06	185.49	332.17	339.06	1	24.1	0.87
					avg:	0.85
					std dev:	0.01
					% rel std:	1.68

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
145.77	100	172.37	157.72	0.1195
138.28	100	164.64	150.15	0.1187
141.56	100	168.21	153.54	0.1198
			avg:	0.1193
			std dev:	0.0005
			% rel std:	0.3891

POROSITY:

n = 0.8603

VOLUMETRIC WATER CONTENT:

theta = 0.4750

INITIAL FAS:

FAS = n-theta

FAS = 0.3853

38.53%

FAS REDUCTION OVER EXPERIMENT:

	cm					
initial heig	21.3	initial FAS (cm^3)	751.73	Final FAS (% of final volume)		32.16%
final heigh	19.3	volume reduction:	183.2	FAS reduction (%)	6.37%	
difference	2	Final FAS (cm^3)	568.53			
volume re	183.2					

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.756297

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

8% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
147.52	201.41	336.91	347.63	1		0.83
127.44	183.47	317.52	327.44	1	24.1	0.85
130.11	188.7	321.08	331.2	1		0.85
					avg:	0.85
					std dev:	0.01
					% rel std:	0.96

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
128.45	100	155.64	140.72	0.1227
132.41	100	159.58	144.59	0.1218
153.92	100	181.14	166.11	0.1219
			avg:	0.1221
			std dev:	0.0004
			% rel std:	0.3298

POROSITY:

n = 0.8555

VOLUMETRIC WATER CONTENT:

theta = 0.4701

INITIAL FAS:

FAS = n-theta

FAS = 0.3855

38.55%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	20.5	initial amount of FAS	723.83	Final FAS (% of final volume)	29.03%
final heigh	17.75	volume reduction:	251.9	FAS reduction (%)	9.52%
difference	2.75	Final FAS (cm^3)	471.93		
volume re	251.9				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.65199

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

10% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
133.48	181.45	320.19	332.94	1		0.79
128.73	180.09	319.71	329.23	1		0.84
122.38	174.2	311.14	322.38	1	24.1	0.82
					avg:	0.82
					std dev:	0.02
					% rel std:	2.69

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
118.41	100	146.23	131.05	0.1264
129.97	100	157.71	142.48	0.1251
135.66	100	163.43	148.1	0.1244
			avg:	0.1253
			std dev:	0.0008
			% rel std:	0.6613

POROSITY:

n = 0.8469

VOLUMETRIC WATER CONTENT:

theta = 0.4551

INITIAL FAS:

FAS = n-theta

FAS = 0.3918

39.18%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	21.5	initial amount of FAS	771.69	Final FAS (% of final volume)	34.13%
final heigh	19.85	volume reduction:	151.14	FAS reduction (%)	5.06%
difference	1.65	Final FAS (cm^3)	620.55		
volume re	151.14				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.804145

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

12% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
138.74	195.72	330.42	338.74	1	24.1	0.87
172.51	227.89	361.98	370.99	1		0.86
129.44	188.46	319.73	329.13	1		0.86
					avg:	0.87
					std dev:	0.01
					% rel std:	0.62

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
140.18	100	168.59	152.97	0.1279
151.3	100	173.88	163.91	0.1261
142.68	100	190.41	155.39	0.1271
			avg:	0.1270
			std dev:	0.0007
			% rel std:	0.5797

POROSITY:

n = 0.8532

VOLUMETRIC WATER CONTENT:

theta = 0.4810

INITIAL FAS:

FAS = n-theta

FAS = 0.3722

37.22%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	22.3	initial amount of FAS	760.22	Final FAS (% of final volume)	33.17%
final heigh	20.95	volume reduction:	123.66	FAS reduction (%)	4.05%
difference	1.35	Final FAS (cm^3)	636.56		
volume re	123.66				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.837336

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

12% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
138.43	193.45	323.34	338.43	1	24.1	0.78
127.45	188.91	312.06	328.02	1		0.79
158.67	225.81	342.28	359.59	1		0.80
					avg:	0.79
					std dev:	0.00
					% rel std:	0.58

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
135.81	100	164.88	148.91	0.131
142.58	100	172.42	156	0.1342
139.47	100	169.04	151.93	0.1246
			avg:	0.1299
			std dev:	0.0040
			% rel std:	3.0717

POROSITY:

n = 0.8358

VOLUMETRIC WATER CONTENT:

theta = 0.4399

INITIAL FAS:

FAS = n-theta

FAS = 0.3959

39.59%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	21.1	initial amount of FAS	765.11	Final FAS (% of final volume)	31.10%
final heigh	18.5	volume reduction:	238.16	FAS reduction (%)	8.49%
difference	2.6	Final FAS (cm^3)	526.95		
volume re	238.16				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.688725

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

16% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
139.08	186.77	329.75	340.87	1		0.81
141.42	197.33	330.58	341.42	1	24.1	0.84
107.5	159.26	296.48	306.88	1		0.83
					avg:	0.83
					std dev:	0.01
					% rel std:	1.40

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
157.42	100	188.97	170.98	0.1356
122.09	100	151.03	134.92	0.1283
154.66	100	184.44	168.01	0.1335
			avg:	0.1325
			std dev:	0.0031
			% rel std:	2.3164

POROSITY:

n = 0.8398

VOLUMETRIC WATER CONTENT:

theta = 0.4599

INITIAL FAS:

FAS = n-theta

FAS = 0.3800

38.00%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	20.8	initial amount of FAS	723.98	Final FAS (% of final volume)	35.52%
final heigh	20	volume reduction:	73.28	FAS reduction (%)	2.48%
difference	0.8	Final FAS (cm^3)	650.70		
volume re	73.28				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.898782

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

18% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
137.29	195	325.77	337.29	1	24.1	0.83
124.45	183.74	311.84	322.81	1		0.84
119.83	177.29	304.28	319.4	1		0.79
					avg:	0.82
					std dev:	0.02
					% rel std:	2.74

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
132.24	100	166.41	146.56	0.1432
144.75	100	175.23	158.4	0.1365
157.36	100	186.27	170.94	0.1358
			avg:	0.1385
			std dev:	0.0033
			% rel std:	2.4084

POROSITY:

n = 0.8317

VOLUMETRIC WATER CONTENT:

theta = 0.4576

INITIAL FAS:

FAS = n-theta

FAS = 0.3741

37.41%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	21	initial amount of FAS	719.64	Final FAS (% of final volume)	34.28%
final heigh	20	volume reduction:	91.6	FAS reduction (%)	3.13%
difference	1	Final FAS (cm^3)	628.04		
volume re	91.6				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.872713

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

20% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
143.28	201.72	328.19	341.57	1		0.81
129.99	191.68	320.06	330.84	1		0.85
133.72	193.78	319.44	333.72	1	24.1	0.81
					avg:	0.82
					std dev:	0.02
					% rel std:	2.33

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
155.52	100	186.77	169.54	0.1402
127.63	100	158.04	142.05	0.1442
162.78	100	194.72	177.15	0.1437
			avg:	0.1427
			std dev:	0.0018
			% rel std:	1.2470

POROSITY:

n = 0.8269

VOLUMETRIC WATER CONTENT:

theta = 0.4583

INITIAL FAS:

FAS = n-theta

FAS = 0.3686

36.86%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	23.3	initial amount of FAS	786.65	Final FAS (% of final volume)	35.47%
final heigh	22.8	volume reduction:	45.8	FAS reduction (%)	1.38%
difference	0.5	Final FAS (cm^3)	740.85		
volume re	45.8				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_t/FAS_o)

0.941778

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

22% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
103.69	164.01	283.05	303.69	1	24.1	0.75
119.73	180.49	297.15	321.01	1		0.72
128.41	192.96	304.92	329.07	1		0.73
					avg:	0.73
					std dev:	0.01
					% rel std:	1.53

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
162.1	100	195.21	176.78	0.1468
148.18	100	180.47	163.04	0.1486
139.42	100	169.38	154.81	0.1539
			avg:	0.1498
			std dev:	0.0030
			% rel std:	2.0122

POROSITY:

n = 0.7949

VOLUMETRIC WATER CONTENT:

theta = 0.4060

INITIAL FAS:

FAS = n-theta

FAS = 0.3889

38.89%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	21.4	initial amount of FAS	762.31	Final FAS (% of final volume)	34.28%
final heigh	19.9	volume reduction:	137.4	FAS reduction (%)	4.61%
difference	1.5	Final FAS (cm^3)	624.91		
volume re	137.4				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.819758

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

24% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
134.57	201.02	324.17	335.78	1	24.1	0.84
138.45	204.58	328.98	337.42	1		0.89
129.72	198.43	319.08	331.81	1		0.84
					avg:	0.86
					std dev:	0.02
					% rel std:	2.36

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
109.87	100	143.81	124.94	0.1507
122.62	100	155.03	138.26	0.1564
137.48	100	169.38	152.61	0.1513
			avg:	0.1528
			std dev:	0.0026
			% rel std:	1.6737

POROSITY:

n = 0.8219

VOLUMETRIC WATER CONTENT:

theta = 0.4771

INITIAL FAS:

FAS = n-theta

FAS = 0.3448

34.48%

FAS REDUCTION OVER EXPERIMENT:

	cm				
initial heig	22.6	initial amount of FAS	713.80	Final FAS (% of final volume)	29.99%
final heigh	21.15	volume reduction:	132.82	FAS reduction (%)	4.49%
difference	1.45	Final FAS (cm^3)	580.98		
volume re	132.82				

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_0)

0.813925

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

26% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
124.18	187.11	315.78	325.66	1		0.86
138.2	199.21	326.5	338.2	1	24.1	0.84
119.68	178.43	309.12	320.75	1		0.83
					avg:	0.85
					std dev:	0.01
					% rel std:	1.54

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
146.57	100	181.91	161.96	0.1539
152.89	100	186.43	168.03	0.1514
139.48	100	174.22	155.18	0.157
			avg:	0.1541
			std dev:	0.0023
			% rel std:	1.4864

POROSITY:

n = 0.8179

VOLUMETRIC WATER CONTENT:

theta = 0.4704

INITIAL FAS:

FAS = n-theta

FAS = 0.3475

34.75%

FAS REDUCTION OVER EXPERIMENT:

	cm					
initial heig	21.55	initial amount of FAS	685.87	Final FAS (% of final volume)		29.69%
final heigh	20	volume reduction:	141.98	FAS reduction (%)	5.06%	
difference	1.55	Final FAS (cm^3)	543.89			
volume re	141.98					

**volume is calculated using 91.6cm^2 as cross-sectional area of reactor cylinder

C/C_0 (FAS_f/FAS_o)

0.792993

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

28% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
138.48	192.73	326.99	338.48	1	24.1	0.83
127.09	187.33	316.42	327.09	1		0.85
141.23	202.19	330.02	341.23	1		0.84
					avg:	0.84
					std dev:	0.01
					% rel std:	1.25

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
156.02	100	193.27	172.74	0.1672
149.22	100	184.01	165.46	0.1624
128.45	100	166.43	144.72	0.1627
			avg:	0.1641
			std dev:	0.0022
			% rel std:	1.3379

POROSITY:

n = 0.8046

VOLUMETRIC WATER CONTENT:

theta = 0.4619

INITIAL FAS:

FAS = n-theta

FAS = 0.3427

34.27%

FAS REDUCTION OVER EXPERIMENT:

	cm					
initial heig	23.15	initial amount of FAS	726.72	Final FAS (% of final volume)		33.55%
final heigh	22.9	volume reduction:	22.9	FAS reduction (%)	0.72%	
difference	0.25	Final FAS (cm^3)	703.82			
volume re	22.9					
	cm					
initial heig	22.5	initial amount of FAS	706.31	Final FAS (% of final volume)		33.38%
final heigh	22.2	volume reduction:	27.48	FAS reduction (%)	0.89%	
difference	0.3	Final FAS (cm^3)	678.83			
volume re	27.48					

C/C_0 (FAS_f/FAS_o) average volume redu 25.19

0.968488

C/C_0 (FAS_f/FAS_o) average final FAS: 691.3256

0.961094

average: 0.964791 average final FAS (%vol) 33.47%

Initial FAS measurements: **used 250 mL flask!

PARTICLE DENSITY:

30% soil

wt flask (g)	wt flask + compost (g)	wt flask+ omp+wate (g)	wt flask + water (200 mL)	density of water at T (g/cm^3)	temp	particle density (g/cm^3)
131.24	186.14	323.42	331.24	1	24.1	0.88
148.75	204.33	333.72	348.75	1		0.79
128.13	180.74	320.55	328.13	1		0.87
					avg:	0.85
					std dev:	0.04
					% rel std:	4.88

DRY BULK DENSITY:

wt flask (g)	volume ask (cm^3	wt flask+ compost (g)	wt dried comp+flsk (g)	dry bulk density (g/cm^3)
155.67	100	193.03	172.02	0.1635
141.37	100	177.68	158.13	0.1676
148.52	100	186.29	164.31	0.1579
			avg:	0.1630
			std dev:	0.0040
			% rel std:	2.4391

POROSITY:

n = 0.8072

VOLUMETRIC WATER CONTENT:

theta = 0.4650

INITIAL FAS:

FAS = n-theta

FAS = 0.3422

34.22%

FAS REDUCTION OVER EXPERIMENT:

	cm					
initial heig	22.5	initial amount of FAS	705.25	Final FAS (% of final volume)		33.33%
final heigh	22.2	volume reduction:	27.48			
difference	0.3	Final FAS (cm^3)	677.77	FAS reduction (%)	0.89%	
volume re	27.48					
	cm					
initial heig	23.15	initial amount of FAS	725.62	Final FAS (% of final volume)		33.50%
final heigh	22.9	volume reduction:	22.9			
difference	0.25	Final FAS (cm^3)	702.72	FAS reduction (%)	0.72%	
volume re	22.9					

C/C_0 (FAS_f/FAS_o) average vol reductio 25.19

0.961035

C/C_0 (FAS_f/FAS_o) average final FAS: 690.2443

0.968441

average: 0.964738 average final FAS (%vol) 33.42%

APPENDIX C-2
TEMPERATURE PROFILES, RELATIVE HEAT GENERATION DATA AND GRAPHS

Time days	0% soil h(cm)	T celsius	mesophilic degree days	chamber T celsius	chamber target
0	20.5	20.3	-	30	35
0.003	20.5	20.3	-	30	35
0.0729	19.8	24.8	-	34.3	35
0.125	19.8	27.9	-	35.2	35
0.1875	19.75	30.3	-	35	35
0.3125	19.7	34.2	-	35.5	35
0.5208	19.5	38.4	0.708	36	35
0.9583	19.3	41.8	2.975	35	35
1.0625	19.3	41.9	0.719	36.2	37
1.4792	19.2	46.9	4.959	39	37
1.9688	19	47.5	6.120	37.8	37
2.0625	18.95	47.8	1.199	39	39
2.3542	18.9	48	3.792	38.2	39
3	18.8	49.5	9.364	40.2	41
3.0625	18.75	49	0.875	40.6	41
3.1354	18.75	49.2	1.035	40	41
3.3125	18.75	49.5	2.568	40.7	41
4	18.7	51.9	11.619	42.5	43
4.0625	18.7	51.8	1.050	42.4	43
4.2292	18.7	52	2.834	44	43
4.4896	18.65	53	4.687	41	43
4.9583	18.6	51.8	7.874	43.2	43
5	18.6	48.8	0.575	44.3	45
5.0625	18.6	49.2	0.888	44.5	45
5.125	18.6	48.7	0.856	46	45
5 2292	18.6	48.5	1.407	45.4	45
5.3542	18.55	48.1	1.638	45.2	45
5.9479	18.55	48.6	8.074	45.6	45
6.1146	18.6	48.8	2.300	45.5	45
6.2917	18.6	48.6	2.409	45.9	45
6.9792	18.5	48.3	9.144	44.7	45
7.4375	18.5	48	5.958	45.1	45
8.0625	18.4	48.1	8.188	45	45
8.4792	18.4	48	5.417	45.1	45
9.0521	18.35	48.2	7.562	44.8	45
9.6458	18.3	48.3	7.896	45.1	45
10.0417	18.3	48.5	5.345	44.6	45
10.1458	18.3	48	1.353	45.8	45
11.0104	18.2	48.5	11.672	45.2	45
11.3542	18	48	4.469	45	45
12	17.9	47.6	8.137	45.9	45
12.3438	17.85	47.4	4.263	44.8	45
12.9792	17.75	47.6	8.006	45.6	45
13.3125	17.75	47.8	4.266	45	45
14	17.75	48	8.938	45.7	45
		sum:	181.140		

Time days	4% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	23	20.7	-	20.6	35
0.0333	22.4	20.7	-	20.9	35
0.0938	22.3	25.1	-	34.8	35
0.1563	22.3	27.3	-	33.4	35
0.2083	22.3	29.3	-	35	35
0.4167	22	38.5	0.729	35.4	35
1	21.6	42.2	4.200	37.8	37
1.0417	21.55	43.1	0.338	36.4	37
1.1354	21.45	42.8	0.731	37.3	37
1.4271	21.4	42.5	2.188	37.4	37
1.9583	21.2	43.1	4.303	37.2	37
2.0208	21.2	43.2	0.512	39	39
2.0938	21.15	43.3	0.606	39.4	39
2.1667	21.1	43.3	0.605	39.5	39
2.375	21	44.8	2.041	38.9	39
2.9688	20.9	46.1	6.591	39.5	39
3.0625	20.8	46.2	1.049	40.6	41
3.1354	20.85	46.3	0.824	40.8	41
3.4271	20.7	47	3.500	41.1	41
3.9479	20.6	47.3	6.406	41	41
4.0938	20.55	47.3	1.795	42.3	43
4.125	20.55	47.2	0.381	42.6	43
4.1771	20.5	47.7	0.662	42.9	43
4.2604	20.5	48.3	1.108	43.6	43
4.3125	20.5	48.8	0.719	43	43
4.3958	20.5	49.1	1.175	43.5	43
4.9479	20.3	50.5	8.558	43.3	43
5.0938	20.35	50.2	2.218	44.8	45
5.1354	20.35	51.8	0.699	45.8	45
5.2292	20.25	53.4	1.726	45.9	45
5.2813	20.25	53.1	0.943	46.1	45
5.9479	20.25	48.1	8.732	45	45
6	20.2	47.8	0.667	44.4	45
6.0833	20.25	47.8	1.066	44.8	45
6.1979	20.2	48.1	1.501	44.9	45
6.3125	20.2	48.3	1.524	45.3	45
6.9479	20.15	49	8.896	44.5	45
7.0417	20.15	49.3	1.341	44	45
7.25	20.1	51.4	3.416	46	45
7.4063	20.1	48.9	2.173	45.7	45
7.9583	20.05	46.4	6.293	46	45
8.0104	20.05	46.5	0.599	45.8	45
8.0521	20.1	46	0.459	44	45
8.1354	20.05	45.3	0.858	45.6	45
8.2604	20.05	45.4	1.300	44.5	45
8.9479	20	45	6.875	44	45
9.0313	20	45.7	0.892	45.9	45
9.125	20	45.8	1.012	45.2	45
9.2083	20	45.7	0.891	44.8	45
9.2917	20	45.7	0.892	45	45
9.9583	20	45.8	7.199	45	45
10.0104	19.9	46	0.573	44.8	45

Time days	4% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
10.9688	19.8	46.2	10.734	45.4	45
11.1146	19.8	45.9	1.589	44	45
11.9271	19.5	46	8.938	44.4	45
12	19.5	46	0.802	44.5	45
12.375	19.4	46.3	4.237	44.6	45
12.9688	19.4	46.2	6.651	45.4	45
13.0521	19.2	46.5	0.958	45.9	45
13.1667	19.2	46.2	1.284	43.9	45
13.2813	19.2	45	1.146	44.6	45
13.9479	19.15	46	7.333	45.9	45
14	19.1	45.6	0.552	45	45
		sum:	155.989		

Time days	6% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	21.3	20.5	-	20.6	35
0.0333	21.1	20.5	-	20.9	35
0.0938	21	25.7	-	34.8	35
0.1563	21	28.6	-	33.4	35
0.2083	21	28.2	-	35	35
0.4167	20.9	36.4	0.292	35.4	35
1	20.8	42.1	4.141	37.8	37
1.0417	20.75	42.5	0.313	36.4	37
1.1354	20.75	42.8	0.731	37.3	37
1.4271	20.75	41.9	2.013	37.4	37
1.9583	20.7	42.6	4.037	37.2	37
2.0208	20.7	42.8	0.487	39	39
2.0938	20.7	43	0.584	39.4	39
2.1667	20.7	43.1	0.590	39.5	39
2.375	20.6	44	1.875	38.9	39
2.9688	20.55	45.6	6.294	39.5	39
3.0625	20.5	45.8	1.012	40.6	41
3.1354	20.45	45.8	0.787	40.8	41
3.4271	20.4	46.3	3.296	41.1	41
3.9479	20.4	46.7	6.093	41	41
4.0938	20.4	47.2	1.780	42.3	43
4.125	20.4	47	0.374	42.6	43
4.1771	20.36	47.2	0.636	42.9	43
4.2604	20.35	48.1	1.091	43.6	43
4.3125	20.4	48.5	0.703	43	43
4.3958	20.35	49.3	1.191	43.5	43
4.9479	20.35	50.5	8.558	43.3	43
5.0938	20.3	51.5	2.407	44.8	45
5.1354	20.3	52.1	0.711	45.8	45
5.2292	20.2	53.9	1.773	45.9	45
5.2813	20.15	53	0.938	46.1	45
5.9479	20.15	48.3	8.866	45	45
6	20.15	48.2	0.688	44.4	45
6.0833	20.1	48.3	1.108	44.8	45
6.1979	20.1	49	1.604	44.9	45
6.3125	20.15	48.9	1.593	45.3	45
6.9479	20.1	48.7	8.705	44.5	45
7.0417	20.1	49.5	1.360	44	45
7.25	20.05	51.2	3.374	46	45
7.4063	20.05	48.7	2.141	45.7	45
7.9583	20.1	46.7	6.458	46	45
8.0104	20.1	46.5	0.599	45.8	45
8.0521	20.05	46.2	0.467	44	45
8.1354	20.05	45.8	0.900	45.6	45
8.2604	20.05	45.8	1.350	44.5	45
8.9479	20	44.5	6.531	44	45
9.0313	19.95	46	0.917	45.9	45
9.125	19.9	46.1	1.040	45.2	45
9.2083	19.95	46.3	0.941	44.8	45
9.2917	19.95	46.3	0.942	45	45
9.9583	19.9	46.2	7.466	45	45

Time days	6% soil h(cm)	T (°C)	mes-ophilic degree days	chamber T celsius	chamber target
10.0104	19.85	47	0.625	44.8	45
10.9688	19.8	46.6	11.117	45.4	45
11.1146	19.75	46.3	1.648	44	45
11.9271	19.5	46.3	9.181	44.4	45
12	19.5	46.1	0.809	44.5	45
12.375	19.5	46.4	4.275	44.6	45
12.9688	19.5	46.5	6.829	45.4	45
13.0521	19.3	46.3	0.941	45.9	45
13.1667	19.3	46	1.261	43.9	45
13.2813	19.3	45.1	1.157	44.6	45
13.9479	19.3	46	7.333	45.9	45
14	19.3	45.5	0.547	45	45
		sum:	155.485		

Time days	8% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	20.6	19.8	-	30	35
0.003	20	19.8	-	30	35
0.0729	19.9	24	-	34.3	35
0.125	19.75	26.9	-	35.2	35
0.1875	19.7	29.8	-	35	35
0.3125	19.6	33	-	35.5	35
0.5208	19.4	36.6	0.333	36	35
0.9583	19	38.4	1.487	35	35
1.0625	19	38.5	0.365	36.2	37
1.4792	18.9	43.9	3.709	39	37
1.9688	18.7	45.2	4.994	37.8	37
2.0625	18.7	44.8	0.918	39	39
2.3542	18.6	45.1	2.946	38.2	39
3	18.55	45.8	6.975	40.2	41
3.0625	18.55	45	0.625	40.6	41
3.1354	18.5	45.5	0.765	40	41
3.3125	18.5	45.8	1.913	40.7	41
4	18.5	48.5	9.281	42.5	43
4.0625	18.5	48	0.813	42.4	43
4.2292	18.45	48.7	2.284	44	43
4.4896	18.4	46.1	2.890	41	43
4.9583	18.4	45.8	5.062	43.2	43
5	18.4	46.1	0.463	44.3	45
5.0625	18.35	45.8	0.675	44.5	45
5.125	18.35	45.8	0.675	46	45
5.2292	18.4	46.9	1.240	45.4	45
5.3542	18.35	46.8	1.475	45.2	45
5.9479	18.3	46.7	6.946	45.6	45
6.1146	18.36	46.3	1.884	45.5	45
6.2917	18.3	46.5	2.037	45.9	45
6.9792	18.25	46.1	7.631	44.7	45
7.4375	18.25	45.8	4.950	45.1	45
8.0625	18.3	46.1	6.938	45	45
8.4792	18.3	46	4.584	45.1	45
9.0521	18.3	46	6.302	44.8	45
9.6458	18.3	46	6.531	45.1	45
10.0417	18.3	46.5	4.553	44.6	45
10.1458	18.25	45.9	1.135	45.8	45
11.0104	18.25	46.1	9.597	45.2	45
11.3542	18.05	46.4	3.919	45	45
12	18	46.3	7.298	45.9	45
12.3438	17.95	45.8	3.713	44.8	45
12.9792	17.95	46.4	7.244	45.6	45
13.3125	17.95	46.5	3.833	45	45
14	17.9	46.6	7.975	45.7	45
		sum:	146.955		

Time days	10% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0.0000	22.5	21.3	-	30.8	35
0.0035	22.15	21.3	-	30.8	35
0.0833	22	24.6	-	34.2	35
0.1250	22.1	26.2	-	34.9	35
0.2083	21.95	30.2	-	35.7	35
0.2813	21.9	32.2	-	34	35
0.3333	21.9	35.1	0.005	35.5	35
0.4479	21.8	36	0.115	35	35
0.9792	21.7	36.6	0.850	35.7	35
1.0208	21.7	37.1	0.087	36.5	37
1.0833	21.65	37.3	0.144	38	37
1.1667	21.65	37.4	0.200	36.2	37
1.2083	21.6	38.1	0.129	36.7	37
1.3021	21.45	38.3	0.309	37.1	37
1.3854	21.4	38.7	0.308	37	37
1.4896	21.4	38.5	0.365	36.9	37
1.6250	21.35	38.6	0.488	36.9	37
1.9896	21.2	39	1.458	36.8	37
2.0625	21.2	39.7	0.343	39.1	39
2.1250	21.05	40	0.313	39.1	39
2.2500	21	40.3	0.662	38.4	39
2.9896	20.9	40.9	4.364	38.9	39
3.0208	20.8	41.9	0.215	41	41
3.1250	20.75	42	0.729	41.5	41
3.3333	20.75	42.4	1.541	41.1	41
3.4583	20.75	43.1	1.013	40.8	41
3.9896	20.7	43.9	4.728	41.1	41
4.0313	20.7	44.1	0.379	43.3	43
4.1250	20.65	44.4	0.881	43	43
4.3438	20.6	45.6	2.319	43.6	43
4.9688	20.6	46	6.875	43.1	43
5.0417	20.65	46.2	0.817	44.6	45
5.2917	20.65	46.1	2.775	44.5	45
5.3854	20.7	46.8	1.106	45	45
5.4479	20.7	46.9	0.744	45.5	45
6.0625	20.6	47.2	7.498	44.8	45
6.2917	20.5	47.5	2.865	44.8	45
7.1146	20.4	47.9	10.616	45	45
7.2917	20.4	48.5	2.391	45.2	45
7.5417	20.45	48.6	3.400	45	45
8.1563	20.4	48.4	8.235	45.5	45
8.375	20.45	47.6	2.756	45.4	45
9.0417	20.40	47.3	8.200	45.2	45
9.2083	20.40	47	1.999	45.1	45
9.3542	20.40	46.8	1.722	44.7	45
10.0417	20.40	46.4	7.837	45.3	45
10.2708	20.40	46.6	2.658	45.6	45
10.5	20.40	46.4	2.613	45.1	45
11.0417	20.40	46.7	6.338	44.9	45
11.2708	20.40	46.7	2.680	44.5	45

Time days	10% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12.0417	20.4	46.7	9.020	44.8	45
12.2188	20.4	46.5	2.037	45.1	45
12.5521	20.4	46.4	3.800	45.2	45
13.0417	20.35	46.3	5.532	45.4	45
13.1042	20.35	45.9	0.681	44.5	45
14.0000	20.3	46	9.854	45	45
		sum:	135.593		

Time days	12% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	22.3	25.9	-	28.5	35
0.003	22.15	25.9	-	28.5	35
0.0625	22.2	28.3	-	33.6	35
0.1042	22.2	29	-	33.5	35
0.1458	22.2	29.8	-	33.8	35
0.25	22.15	31.6	-	34	35
0.3958	22.1	35	0.000	35.2	35
0.9792	22	37.5	1.459	36.6	37
1.125	21.95	38	0.437	35.8	37
1.25	21.9	38.6	0.450	34.9	37
1.9896	21.85	40.5	4.068	35.9	37
2.0417	21.8	40.7	0.297	38.9	39
2.0833	21.8	41	0.250	38.6	39
2.2917	21.8	41.9	1.438	38.2	39
3	21.7	42.6	5.383	38.5	41
3.0729	21.7	42.9	0.576	38.5	41
3.1146	21.7	42.9	0.329	37.2	41
3.4792	21.7	43.2	2.990	38.1	41
3.5028	21.6	43.8	0.208	39.8	41
3.9479	21.5	45.8	4.807	41	41
3.9896	21.5	45.8	0.450	42.6	43
4.1146	21.5	46.6	1.450	42.1	43
4.1979	21.45	47	1.000	42.5	43
4.4688	21.4	47.9	3.495	43.5	43
4.9688	21.3	48.4	6.700	43.2	43
5.0938	21.3	49.1	1.763	43.6	45
5.5	21	49.2	5.768	45.1	45
5.9792	21.1	49.5	6.948	45	45
6.0729	21.05	49.3	1.340	45.3	45
6.25	21.1	48.9	2.462	45.5	45
6.4792	21.1	48.9	3.186	45.1	45
6.9792	21.1	48.7	6.850	45.5	45
7.0521	21.1	49.1	1.028	44.6	45
7.125	21.05	48.7	0.999	45.1	45
7.4271	21	48.9	4.199	44.7	45
7.9792	21	49.2	7.840	47.1	45
8.0833	21	48.8	1.437	44.8	45
8.1771	21	48.5	1.266	46	45
8.3542	21	48.4	2.373	44.8	45
8.9792	21	48.4	8.375	45.3	45
9.125	21	47.6	1.837	45.4	45
9.3542	21	47.5	2.865	44.8	45
9.9896	21	47.3	7.815	45.3	45
10.1667	21	46.8	2.090	44.9	45
10.9792	21	46.9	9.669	45.2	45
11.1042	21	46.9	1.488	43.4	45
11.5521	21	47	5.375	44.1	45
12	21	47.4	5.554	45.3	45
12.0833	20.95	47.5	1.041	45.5	45

Time days	12% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12.4271	20.95	47.5	4.297	45.3	45
12.9792	20.95	47.5	6.901	45.4	45
13.1146	20.95	47.4	1.679	45.3	45
13.2708	20.95	47.1	1.890	45.3	45
14	20.95	46.9	8.677	45.1	45
		sum:	152.798		

Time days	14 % soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0.0000	22	21.8	-	30.8	35
0.0035	21.7	21.8	-	30.8	35
0.0833	21.7	25.2	-	34.2	35
0.1250	21.65	26.9	-	34.9	35
0.2083	21.6	29	-	35.7	35
0.2813	21.6	30.2	-	34	35
0.3333	21.6	35.7	0.036	35.5	35
0.4479	21.6	36	0.115	35	35
0.9792	21.5	36.5	0.797	35.7	35
1.0208	21.5	36.5	0.062	36.5	37
1.0833	21.45	37.2	0.138	38	37
1.1667	21.4	37.3	0.192	36.2	37
1.2083	21.4	37.9	0.121	36.7	37
1.3021	21.2	37.9	0.272	37.1	37
1.3854	21.2	38	0.250	37	37
1.4896	21.2	38.3	0.344	36.9	37
1.6250	21.2	38.5	0.474	36.9	37
1.9896	21.05	39.2	1.531	36.8	37
2.0625	21.1	39.8	0.350	39.1	39
2.1250	21	39.8	0.300	39.1	39
2.2500	20.85	39.8	0.600	38.4	39
2.9896	20.7	40.5	4.068	38.9	39
3.0208	20.55	41.9	0.215	41	41
3.1250	20.6	41.8	0.709	41.5	41
3.3333	20.5	42.4	1.541	41.1	41
3.4583	20.5	43.1	1.013	40.8	41
3.9896	20.45	43.9	4.728	41.1	41
4.0313	20.45	43.9	0.371	43.3	43
4.1250	20.45	44.4	0.881	43	43
4.3438	20.4	45.8	2.362	43.6	43
4.9688	20.4	45.8	6.750	43.1	43
5.0417	20.3	46	0.802	44.6	45
5.2917	20.3	46.2	2.800	44.5	45
5.3854	20.3	46.3	1.059	45	45
5.4479	20.3	46.1	0.694	45.5	45
6.0625	20.2	47.5	7.682	44.8	45
6.2917	20.1	47.6	2.888	44.8	45
7.1146	20.05	47.8	10.533	45	45
7.2917	20	48.1	2.320	45.2	45
7.5417	20	48.5	3.375	45	45
8.1563	20	48	7.990	45.5	45
8.375	20	47.8	2.800	45.4	45
9.0417	19.8	47.1	8.067	45.2	45
9.2083	19.8	46.8	1.966	45.1	45
9.3542	19.8	46.6	1.692	44.7	45
10.0417	19.8	46.9	8.181	45.3	45
10.2708	19.8	46.5	2.635	45.6	45
10.5	19.8	46.8	2.705	45.1	45
11.0417	19.75	46.7	6.338	44.9	45
11.2708	19.75	46.6	2.658	44.5	45

Time days	14 % soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12.0417	19.65	46.8	9.097	44.8	45
12.2188	19.65	46.9	2.107	45.1	45
12.5521	19.65	46.4	3.800	45.2	45
13.0417	19.6	46.2	5.484	45.4	45
13.1042	19.6	46	0.688	44.5	45
14.0000	19.55	45.9	9.764	45	45
		SUM:	136.343		

Time days	16% soil ht	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	21.95	19.6	-	30	35
0.003	21.95	19.6	-	30	35
0.0729	21.7	23.1	-	34.3	35
0.125	21.7	25.8	-	35.2	35
0.1875	21.7	28.7	-	35	35
0.3125	21.6	32.5	-	35.5	35
0.5208	21.5	36	0.208	36	35
0.9583	21.5	37.8	1.225	35	35
1.0625	21.4	37.9	0.302	36.2	37
1.4792	21.3	43.5	3.542	39	37
1.9688	21.2	44.5	4.651	37.8	37
2.0625	21.2	44.4	0.881	39	39
2.3542	21.2	44.9	2.888	38.2	39
3	21.15	45.6	6.845	40.2	41
3.0625	21.15	45.1	0.631	40.6	41
3.1354	21.1	45.7	0.780	40	41
3.3125	21.1	46	1.948	40.7	41
4	21.1	47.9	8.869	42.5	43
4.0625	21.1	48	0.813	42.4	43
4.2292	21	48.6	2.267	44	43
4.4896	21	48.2	3.437	41	43
4.9583	21	45.7	5.015	43.2	43
5	21	45.7	0.446	44.3	45
5.0625	21	46	0.688	44.5	45
5.125	21	45.8	0.675	46	45
5.2292	21	46.9	1.240	45.4	45
5.3542	21	46.6	1.450	45.2	45
5.9479	21	47.7	7.540	45.6	45
6.1146	21	47.7	2.117	45.5	45
6.2917	21	47.7	2.249	45.9	45
6.9792	21	47.6	8.663	44.7	45
7.4375	21	47.5	5.729	45.1	45
8.0625	21	47.8	8.000	45	45
8.4792	21	47.9	5.375	45.1	45
9.0521	21	46	6.302	44.8	45
9.6458	21	45.9	6.471	45.1	45
10.0417	21	46	4.355	44.6	45
10.1458	21	46.2	1.166	45.8	45
11.0104	20.95	45.5	9.078	45.2	45
11.3542	20.4	46.2	3.851	45	45
12	20.4	46	7.104	45.9	45
12.3438	20.4	45.6	3.644	44.8	45
12.9792	20.4	46.1	7.053	45.6	45
13.3125	20.4	46.2	3.733	45	45
14	20.4	46.5	7.906	45.7	45
		sum:	149.138		

Time days	18% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	21	26.2	-	28.5	35
0.003	20.8	26.2	-	28.5	35
0.0625	20.8	29.1	-	33.6	35
0.1042	20.8	29.6	-	33.5	35
0.1458	20.8	30.3	-	33.8	35
0.25	20.6	32.2	-	34	35
0.3958	20.5	34.9	-	35.2	35
0.9792	20.35	37.2	1.283	36.6	37
1.125	20.35	38.4	0.496	35.8	37
1.25	20.3	37.9	0.362	34.9	37
1.9896	20.3	39.5	3.328	35.9	37
2.0417	20.3	40	0.261	38.9	39
2.0833	20.3	40.2	0.216	38.6	39
2.2917	20.3	40.5	1.146	38.2	39
3	20.25	41.4	4.533	38.5	41
3.0729	20.25	42.2	0.525	38.5	41
3.1146	20.25	41.7	0.279	37.2	41
3.4792	20.25	42.1	2.589	38.1	41
3.5028	20.2	42.7	0.182	39.8	41
3.9479	20.2	44.2	4.095	41	41
3.9896	20.2	43.9	0.371	42.6	43
4.1146	20.1	45	1.250	42.1	43
4.1979	20.2	45	0.833	42.5	43
4.4688	20.15	45.9	2.953	43.5	43
4.9688	20.1	46.8	5.900	43.2	43
5.0938	20.15	47.3	1.537	43.6	45
5.5	20.2	48.1	5.321	45.1	45
5.9792	20.2	48.8	6.613	45	45
6.0729	20.05	48.8	1.293	45.3	45
6.25	20.05	48.3	2.355	45.5	45
6.4792	20	48.5	3.094	45.1	45
6.9792	20	48.5	6.750	45.5	45
7.0521	20	48.5	0.984	44.6	45
7.125	20	48.2	0.962	45.1	45
7.4271	19.95	48.4	4.048	44.7	45
7.9792	20	49.1	7.785	47.1	45
8.0833	20	48.5	1.405	44.8	45
8.1771	20	48.7	1.285	46	45
8.3542	19.95	47.9	2.285	44.8	45
8.9792	20.05	47.9	8.063	45.3	45
9.125	20	47.7	1.852	45.4	45
9.3542	20	47.4	2.842	44.8	45
9.9896	20	46.9	7.561	45.3	45
10.1667	20	46.6	2.054	44.9	45
10.9792	20	46.9	9.669	45.2	45
11.1042	20	46.8	1.475	43.4	45
11.5521	20	46.9	5.330	44.1	45
12	20	47.8	5.733	45.3	45

Time days	18% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12.0833	20	47.6	1.050	45.5	45
12.4271	20	47.6	4.332	45.3	45
12.9792	20	47.4	6.846	45.4	45
13.1146	20	46.8	1.598	45.3	45
13.2708	20	47	1.874	45.3	45
14	20	46.7	8.532	45.1	45
		sum:	145.131		

Time days	20% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	23.3	24.3	-	25.9	35
0.003	23.2	24.3	-	25.9	35
0.125	23.3	31.8	-	35.1	35
0.4167	23.3	35.7	0.204	34.8	35
0.9479	23.3	35.8	0.425	33.8	35
1	23.3	35.4	0.021	36.4	37
1.125	23.2	37.3	0.288	37.4	37
1.344	23.2	38	0.657	36.8	37
1.9688	23.2	39.7	2.937	36.9	37
2.0833	23.15	40.2	0.595	37.4	39
2.4271	23.15	40.4	1.857	40.4	39
2.9479	23.15	41.6	3.437	38.3	39
3.0938	23.15	42.2	1.050	40.2	41
4.2083	23.2	42	7.802	40.9	41
4.9583	23.2	42.8	5.850	40.1	41
5.2813	23.2	43	2.584	42.8	43
5.5	23.2	44.3	2.034	43.1	43
5.9903	23.2	43.9	4.364	43.2	43
6.1771	23.2	45.1	1.887	45.2	45
6.9688	23.2	46.5	9.105	44.9	45
7.1771	23.2	46.9	2.479	44.8	45
7.3021	23	47	1.500	44.7	45
8.0938	23	47	9.500	44.9	45
9.0104	22.95	46.2	10.266	44.3	45
9.1354	23	46.3	1.412	46	45
10.0208	23	46.4	10.094	45.5	45
10.0521	23	46.1	0.347	45.8	45
10.1701	22.95	46.5	1.357	46	45
11	22.95	45.3	8.548	44	45
11.1042	22.95	45.3	1.073	44	45
11.9688	22.95	46.3	9.770	45.8	45
12.0556	22.95	46.1	0.963	45.6	45
12.2083	22.9	45.9	1.664	45	45
12.3542	22.8	45.9	1.590	44.4	45
12.9583	22.8	45.9	6.585	45.7	45
13.0833	22.8	45.9	1.363	45.7	45
13.2083	22.8	45.5	1.313	45.6	45
		sum:	114.920		

Time days	22% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	21.4	25.6	-	28.5	35
0.003	21.2	25.6	-	28.5	35
0.0625	21.2	27.5	-	33.6	35
0.1042	21.2	28.7	-	33.5	35
0.1458	21.2	29.4	-	33.8	35
0.25	21.2	31.7	-	34	35
0.3958	21.2	34	-	35.2	35
0.9792	21.1	37.7	1.575	36.6	37
1.125	21.1	37.5	0.365	35.8	37
1.25	21.05	38.5	0.438	34.9	37
1.9896	21	40.3	3.920	35.9	37
2.0417	20.9	40.6	0.292	38.9	39
2.0833	20.95	40.9	0.245	38.6	39
2.2917	20.9	41.3	1.313	38.2	39
3	20.85	42.7	5.454	38.5	41
3.0729	20.8	42.6	0.554	38.5	41
3.1146	20.8	41.9	0.288	37.2	41
3.4792	20.8	43	2.917	38.1	41
3.5028	20.8	43	0.189	39.8	41
3.9479	20.7	44.9	4.406	41	41
3.9896	20.7	44.5	0.396	42.6	43
4.1146	20.6	45.4	1.300	42.1	43
4.1979	20.7	45.5	0.875	42.5	43
4.4688	20.6	46.6	3.142	43.5	43
4.9688	20.6	46.8	5.900	43.2	43
5.0938	20.55	47.6	1.575	43.6	45
5.5	20.5	48.5	5.484	45.1	45
5.9792	20.35	49	6.709	45	45
6.0729	20.3	48.9	1.302	45.3	45
6.25	20.3	48.8	2.444	45.5	45
6.4792	20.3	48.5	3.094	45.1	45
6.9792	20.2	48.4	6.700	45.5	45
7.0521	20.15	48.7	0.999	44.6	45
7.125	20.2	48.4	0.977	45.1	45
7.4271	20.15	48.6	4.109	44.7	45
7.9792	20.1	48.7	7.564	47.1	45
8.0833	20.1	48.6	1.416	44.8	45
8.1771	20.1	48.5	1.266	46	45
8.3542	20.05	48	2.302	44.8	45
8.9792	20.1	47.7	7.938	45.3	45
9.125	20	47.5	1.822	45.4	45
9.3542	20	47	2.750	44.8	45
9.9896	20	46.9	7.561	45.3	45
10.1667	20	46.5	2.037	44.9	45
10.9792	20	46.8	9.588	45.2	45
11.1042	20	46.9	1.488	43.4	45
11.5521	20	47.1	5.420	44.1	45

Time days	22% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12	20	47.2	5.464	45.3	45
12.0833	19.95	47.9	1.075	45.5	45
12.4271	19.95	48.1	4.504	45.3	45
12.9792	19.95	47.9	7.122	45.4	45
13.1146	19.85	48	1.760	45.3	45
13.2708	19.9	47.9	2.015	45.3	45
14	19.9	47.9	9.407	45.1	45
		sum:	149.458		

Time days	24% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
0	22.6	25.5	-	28.5	35
0.003	22.45	25.5	-	28.5	35
0.0625	22.45	27.8	-	33.6	35
0.1042	22.5	28.9	-	33.5	35
0.1458	22.5	29.7	-	33.8	35
0.25	22.5	31.8	-	34	35
0.3958	22.4	35.2	0.029	35.2	35
0.9792	22.3	37.9	1.692	36.6	37
1.125	22.3	38.4	0.496	35.8	37
1.25	22.3	38.9	0.487	34.9	37
1.9896	22.1	40.7	4.216	35.9	37
2.0417	22.1	40.8	0.302	38.9	39
2.0833	22.1	41.2	0.258	38.6	39
2.2917	22.1	42.2	1.500	38.2	39
3	22.1	42.7	5.454	38.5	41
3.0729	22	43	0.583	38.5	41
3.1146	22	42.6	0.317	37.2	41
3.4792	22	43.3	3.026	38.1	41
3.5028	21.95	43.7	0.205	39.8	41
3.9479	21.9	45.8	4.807	41	41
3.9896	21.9	45.5	0.438	42.6	43
4.1146	21.95	46.4	1.425	42.1	43
4.1979	21.9	46.6	0.966	42.5	43
4.4688	21.9	47.5	3.386	43.5	43
4.9688	21.8	48.1	6.550	43.2	43
5.0938	21.7	48.5	1.688	43.6	45
5.5	21.75	49.2	5.768	45.1	45
5.9792	21.7	49.5	6.948	45	45
6.0729	21.6	49.5	1.359	45.3	45
6.25	21.55	49.1	2.497	45.5	45
6.4792	21.5	49	3.209	45.1	45
6.9792	21.5	48.7	6.850	45.5	45
7.0521	21.5	49	1.021	44.6	45
7.125	21.5	48.7	0.999	45.1	45
7.4271	21.5	48.8	4.169	44.7	45
7.9792	21.5	49.2	7.840	47.1	45
8.0833	21.45	49.1	1.468	44.8	45
8.1771	21.45	48.6	1.276	46	45
8.3542	21.5	48.1	2.320	44.8	45
8.9792	21.45	48.2	8.250	45.3	45
9.125	21.35	47.5	1.822	45.4	45
9.3542	21.35	47.5	2.865	44.8	45
9.9896	21.3	46.9	7.561	45.3	45
10.1667	21.3	47.2	2.161	44.9	45
10.9792	21.3	47.3	9.994	45.2	45
11.1042	21.25	47.3	1.537	43.4	45
11.5521	21.25	47.9	5.778	44.1	45

Time days	24% soil h(cm)	T (°C)	mesophilic degree days	chamber T celsius	chamber target
12	21.2	48.4	6.002	45.3	45
12.0833	21.2	48.7	1.141	45.5	45
12.4271	21.2	48.6	4.676	45.3	45
12.9792	21.15	48.9	7.674	45.4	45
13.1146	21.1	48.7	1.855	45.3	45
13.2708	21.15	48.7	2.140	45.3	45
14	21.15	48.4	9.771	45.1	45
		sum:	156.776		

Time days	26% soil h(cm)	T (°C)	mesophilic degreedays	chamber T celsius	chamber target
0	21.55	20.8	-	20.6	35
0.0333	21.3	20.8	-	20.9	35
0.0938	21.35	24.5	-	34.8	35
0.1563	21.35	26.6	-	33.4	35
0.2083	21.3	29.7	-	35	35
0.4167	21.3	34.4	-	35.4	35
1	21.3	41.2	3.616	37.8	37
1.0417	21.25	42.1	0.296	36.4	37
1.1354	21.25	42.3	0.684	37.3	37
1.4271	21.25	41.9	2.013	37.4	37
1.9583	21.2	42.7	4.090	37.2	37
2.0208	21.2	43	0.500	39	39
2.0938	21.2	43	0.584	39.4	39
2.1667	21.2	43	0.583	39.5	39
2.375	21.15	44	1.875	38.9	39
2.9688	21.1	45.4	6.176	39.5	39
3.0625	21	45.3	0.965	40.6	41
3.1354	21	45.3	0.751	40.8	41
3.4271	21	45.4	3.034	41.1	41
3.9479	21	46.2	5.833	41	41
4.0938	21	46.7	1.707	42.3	43
4.125	21	46.7	0.365	42.6	43
4.1771	21	47	0.625	42.9	43
4.2604	20.9	47.5	1.041	43.6	43
4.3125	21	48.2	0.688	43	43
4.3958	21	48.5	1.125	43.5	43
4.9479	20.9	49.9	8.226	43.3	43
5.0938	20.9	50.1	2.203	44.8	45
5.1354	20.8	52.2	0.716	45.8	45
5.2292	20.8	53.6	1.745	45.9	45
5.2813	20.8	53	0.938	46.1	45
5.9479	20.8	48	8.666	45	45
6	20.8	47.9	0.672	44.4	45
6.0833	20.75	47.6	1.050	44.8	45
6.1979	20.7	48.1	1.501	44.9	45
6.3125	20.7	47.9	1.478	45.3	45
6.9479	20.65	48.6	8.641	44.5	45
7.0417	20.65	49.3	1.341	44	45
7.25	20.7	51.7	3.479	46	45
7.4063	20.6	49	2.188	45.7	45
7.9583	20.6	46.4	6.293	46	45
8.0104	20.6	46	0.573	45.8	45
8.0521	20.6	46	0.459	44	45
8.1354	20.55	45.3	0.858	45.6	45
8.2604	20.55	45.1	1.263	44.5	45
8.9479	20.5	45.3	7.081	44	45
9.0313	20.5	45.3	0.859	45.9	45
9.125	20.5	45.9	1.021	45.2	45
9.2083	20.45	45.4	0.866	44.8	45
9.2917	20.45	45.7	0.892	45	45
9.9583	20.4	45.3	6.866	45	45

Time days	26% soil h(cm)	T (°C)	mesophilic degreedays	chamber T celsius	chamber target
10.0104	20.4	45.7	0.557	44.8	45
10.9688	20.4	45.3	9.872	45.4	45
11.1146	20.4	45	1.458	44	45
11.9271	20	44.4	7.638	44.4	45
12	20	44.5	0.693	44.5	45
12.375	20	44.8	3.675	44.6	45
12.9688	20	44.8	5.819	45.4	45
		sum:	136.137		

Time (d)	28% soil (anaer) #1 h (cm)	T (°C)	mesophilic degreedays	chamber T, celsius	target temperature
0	21.1	22.7	-	22.1	35
0.00347	19.8	22.7	-	22.1	35
0.125	19.9	27.6	-	28.9	35
0.3333	19.9	33.4	-	34.7	35
0.7917	19.9	35.7	0.321	35.1	35
0.9583	19.9	36.7	0.283	35.3	35
1.0208	19.85	37.4	0.150	36.7	37
1.1458	19.85	38.4	0.425	37.4	37
1.3021	19.85	38.4	0.531	37.1	37
1.8021	19.85	38.6	1.800	36.8	37
1.9375	19.8	37.9	0.393	36.9	37
2	19.7	38.3	0.206	39.2	39
2.1667	19.75	39.4	0.733	39.1	39
2.2917	19.75	39.8	0.600	39	39
2.7708	19.75	39.5	2.156	39.4	39
2.9167	19.75	40.2	0.759	38.8	39
3.0208	19.75	40.3	0.552	41.1	41
3.2083	19.75	41.6	1.238	41	41
3.4167	19.75	41.9	1.438	40.7	41
3.8333	19.75	42.2	3.000	41.1	41
4	19.75	42.3	1.217	43.4	43
4.2083	19.7	43.9	1.854	42.8	43
4.3333	19.7	44.1	1.138	43.3	43
4.7917	19.7	44	4.126	43.1	43
5	19.7	44.2	1.916	45	45
5.2292	19.7	45.5	2.407	45.3	45
5.7917	19.7	45.6	5.963	45.2	45
6	19.65	45.9	2.270	45	45
6.1979	19.65	46.3	2.236	45.2	45
6.375	19.65	46.4	2.019	44.7	45
6.8021	19.6	46.2	4.784	44.9	45
6.9167	19.65	45.8	1.238	45.4	45
7.0625	19.6	45.9	1.589	44.7	45
7.3333	19.6	45.8	2.925	45.2	45
7.8333	19.6	45.8	5.400	45.3	45
		sum:	55.664		

Time	28% soil (anaer) #2		mesophilic	chamber	chamber
days	h (cm)	T (°C)	degreedays	T celsius	target
0	22.2	24.2	-	25.9	35
0.003	21.9	24.2	-	25.9	35
0.125	21.9	30.8	-	35.1	35
0.4167	21.9	32.1	-	34.8	35
0.9479	21.9	32.9	-	33.8	35
1	21.9	32.9	-	36.4	37
1.125	21.85	34.4	-	37.4	37
1.344	21.8	35.1	0.022	36.8	37
1.9688	21.7	35.9	0.562	36.9	37
2.0833	21.7	36.7	0.195	37.4	39
2.4271	21.7	37.5	0.859	40.4	39
2.9479	21.65	38.2	1.667	38.3	39
3.0938	21.6	38.4	0.496	40.2	41
4.2083	21.6	39.5	5.015	40.9	41
4.9583	21.6	40.3	3.975	40.1	41
5.2813	21.6	40.5	1.776	42.8	43
5.5	21.6	41	1.312	43.1	43
5.9903	21.6	42.5	3.677	41.2	43
6.1771	21.55	43.8	1.644	45.2	45
6.9688	21.55	44.2	7.284	44.9	45
7.1771	21.55	43.9	1.854	44.8	45
		sum:	30.339		

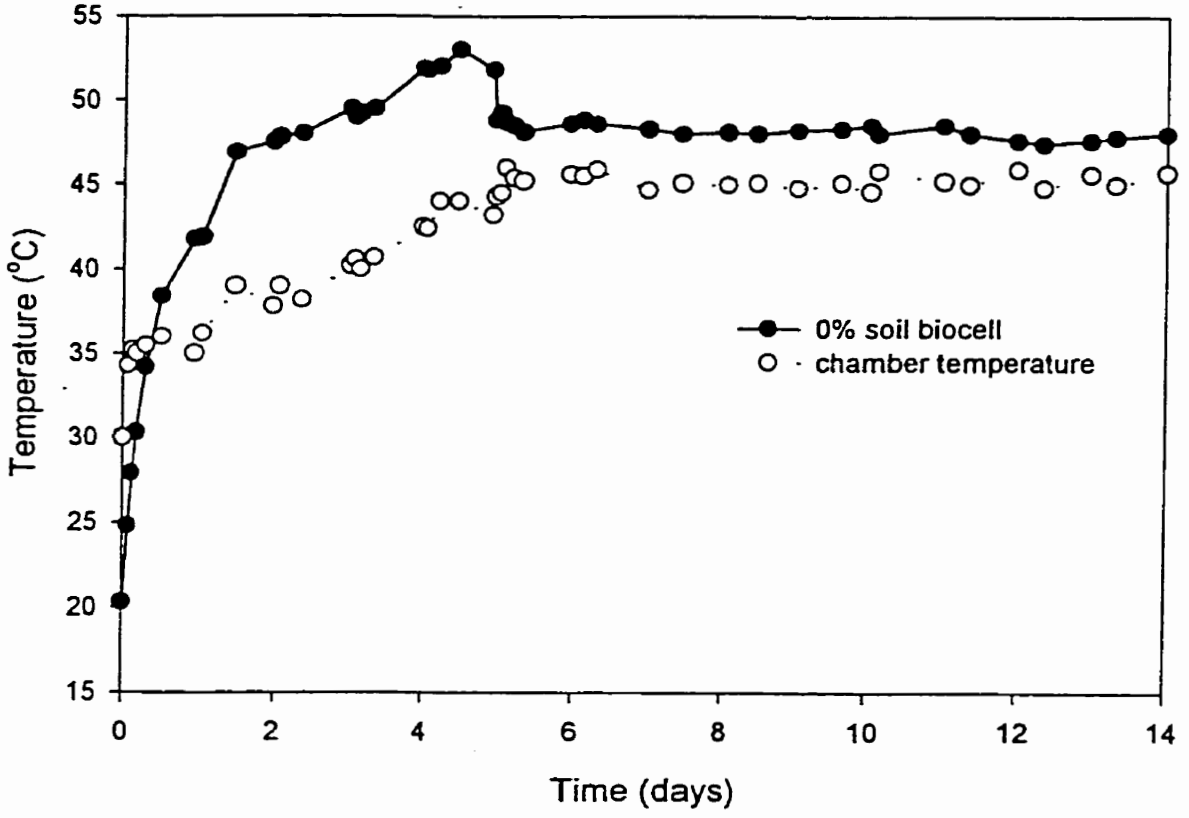
average mesophilic degree days: 43.00

Time days	30% (anaerobic) #1 h(cm)	T celsius	mesophilic degree days	chamber T celsius	chamber target
0	22.5	24.6	-	25.9	35
0.003	22.4	24.6	-	25.9	35
0.125	22.5	32	-	35.1	35
0.4167	22.5	36	0.292	34.8	35
0.9479	22.5	35.9	0.478	33.8	35
1	22.5	35.5	0.026	36.4	37
1.125	22.5	37.1	0.263	37.4	37
1.344	22.3	38.1	0.679	36.8	37
1.9688	22.4	39.7	2.937	36.9	37
2.0833	22.4	40.1	0.584	37.4	39
2.4271	22.4	40.6	1.925	40.4	39
2.9479	22.4	41.1	3.177	38.3	39
3.0938	22.35	41.4	0.934	40.2	41
4.2083	22.3	41.4	7.133	40.9	41
4.9583	22.4	42.3	5.475	40.1	41
5.2813	22.4	42.5	2.422	42.8	43
5.5	22.4	43.8	1.925	43.1	43
5.9903	22.4	43.1	3.971	43.2	43
6.1771	22.4	44.5	1.775	45.2	45
6.9688	22.3	45.9	8.630	44.9	45
7.1771	22.3	45.7	2.229	44.8	45
7.3021	22.2	45.8	1.350	44.7	45
8.0938	22.2	46	8.709	44.9	45
9.0104	22.2	45.4	9.533	44.3	45
9.1354	22.2	45.8	1.350	46	45
10.0208	22.2	45.5	9.297	45.5	45
		sum:	75.091		

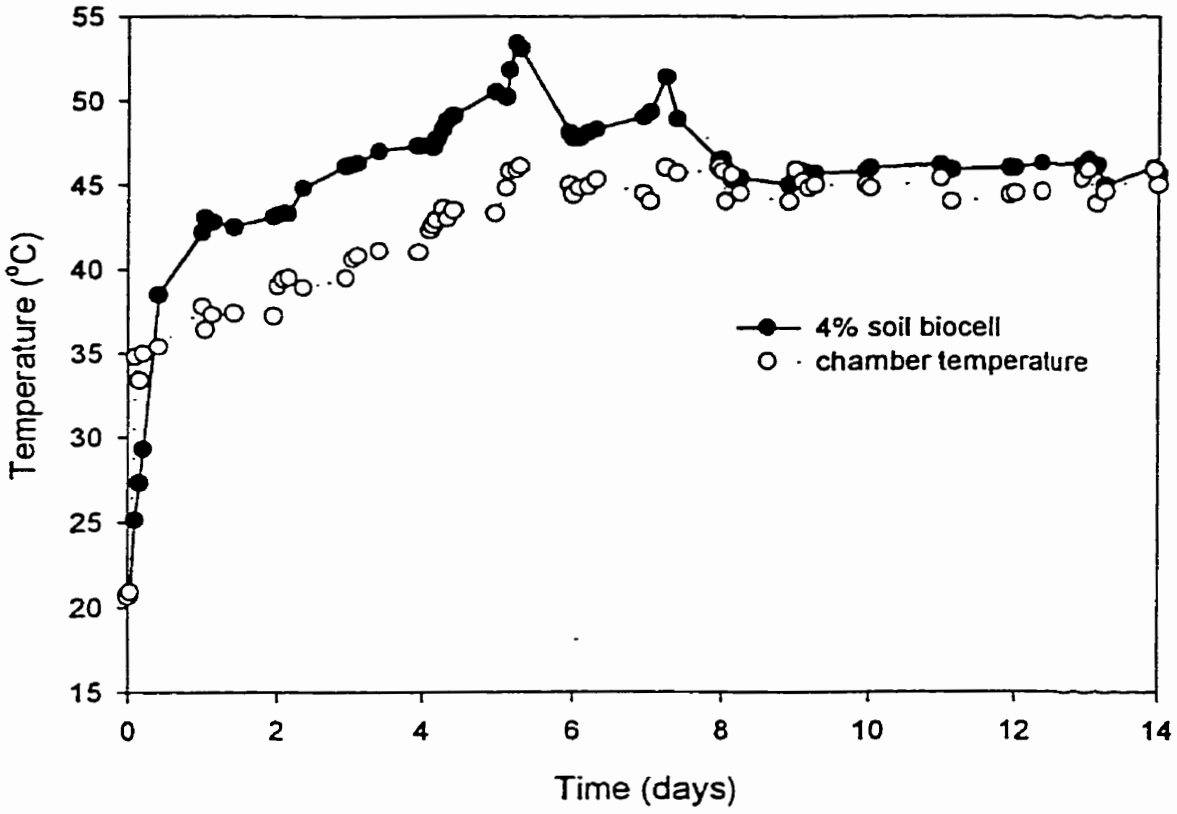
average mesophilic degree day 73.33

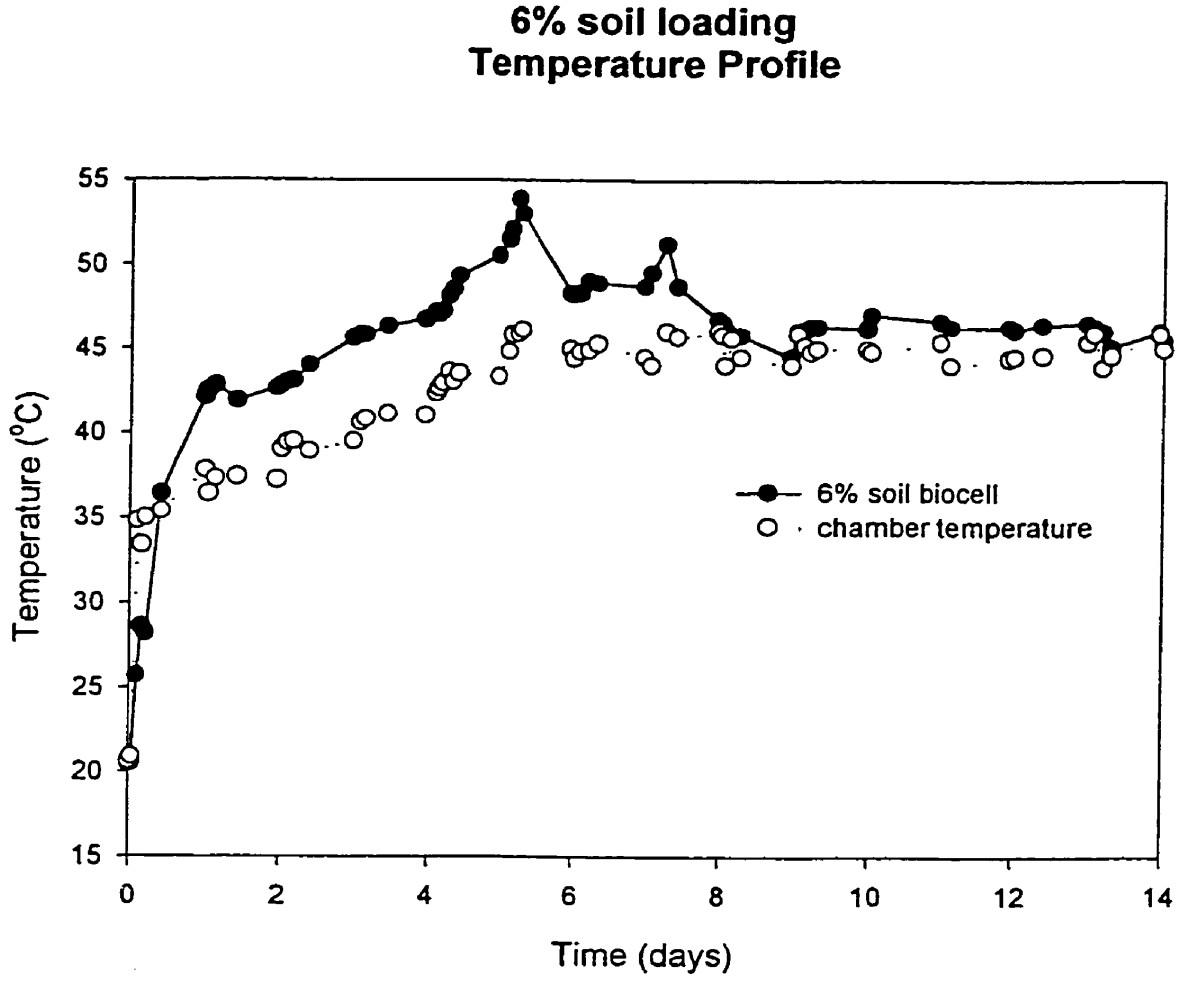
Time	30% anaer #2		mesophilic	chamber	chamber
days	h(cm)	T celsius	degree days	T celsius	target
0	23.15	20.5	-	20.6	35
0.0333	23.15	20.5	-	20.9	35
0.0938	23.1	24.7	-	34.8	35
0.1563	23.1	26.8	-	33.4	35
0.2083	23.1	29	-	35	35
0.4167	23.1	34	-	35.4	35
1	23.1	39.3	2.508	37.8	37
1.0417	23.1	39.1	0.171	36.4	37
1.1354	23.05	38.8	0.356	37.3	37
1.4271	23	38.7	1.079	37.4	37
1.9583	23	39.2	2.231	37.2	37
2.0208	23	39.8	0.300	39	39
2.0938	23	39.6	0.336	39.4	39
2.1667	23	40.2	0.379	39.5	39
2.375	23	40.5	1.146	38.9	39
2.9688	23	41.6	3.919	39.5	39
3.0625	22.95	41.6	0.618	40.6	41
3.1354	22.95	41.6	0.481	40.8	41
3.4271	22.9	42.6	2.217	41.1	41
3.9479	22.95	42.8	4.062	41	41
4.0938	23	43	1.167	42.3	43
4.125	23	42.7	0.240	42.6	43
4.1771	22.9	43.6	0.448	42.9	43
4.2604	22.9	44.7	0.808	43.6	43
4.3125	22.9	45.1	0.526	43	43
4.3958	22.9	45.1	0.841	43.5	43
4.9479	22.8	46.7	6.460	43.3	43
5.0938	22.9	47.7	1.853	44.8	45
5.1354	22.8	49.5	0.603	45.8	45
5.2292	22.8	49.6	1.369	45.9	45
5.2813	22.8	49.3	0.745	46.1	45
5.9479	22.85	45.1	6.733	45	45
6	22.85	45.2	0.531	44.4	45
6.0833	22.85	45.3	0.858	44.8	45
6.1979	22.8	46.1	1.272	44.9	45
6.3125	22.8	45.8	1.238	45.3	45
6.9479	22.8	46.6	7.371	44.5	45
7.0417	22.8	47.2	1.144	44	45
7.25	22.8	48.8	2.875	46	45
7.4063	22.8	46.3	1.766	45.7	45
7.9583	22.9	44.6	5.299	46	45
8.0104	22.9	44.6	0.500	45.8	45
8.0521	22.9	43.9	0.371	44	45
8.1354	22.9	43.1	0.675	45.6	45
8.2604	22.9	43.4	1.050	44.5	45
8.9479	22.9	42.3	5.019	44	45
		sum:	71.567		

0% soil loading
Temperature Profile

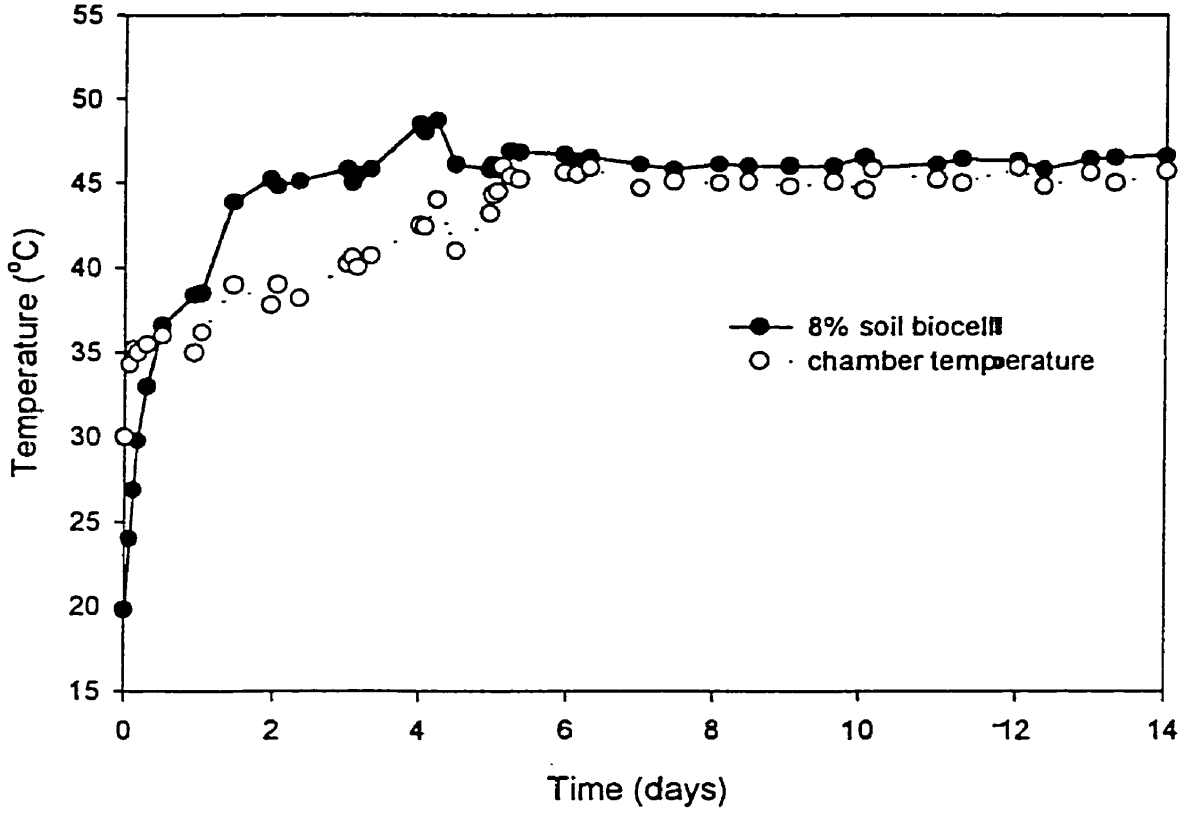


4% soil loading
Temperature Profile

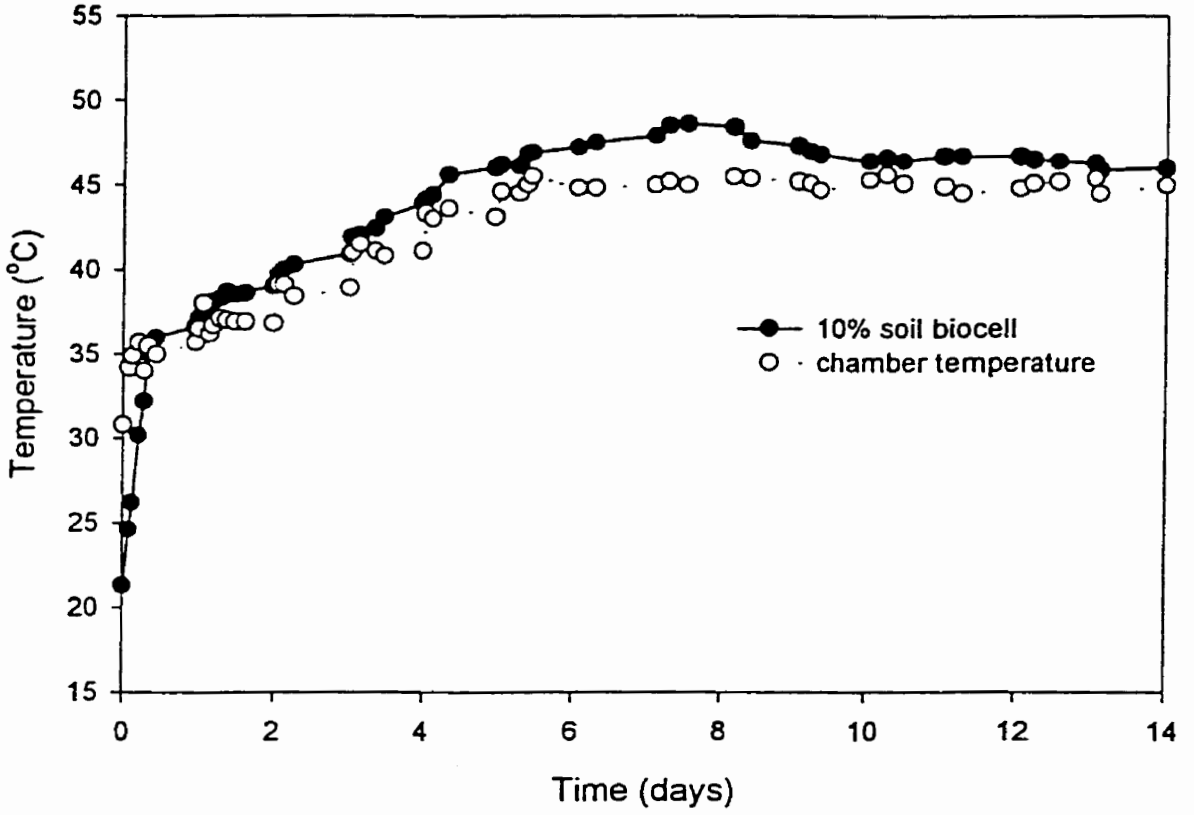



6% soil loading
Temperature Profile
Temperature (°C)
55
50
45
40
35
30
25
20
15
0
2
4
6
8
10
12
14
Time (days)
6% soil biocell
chamber temperature

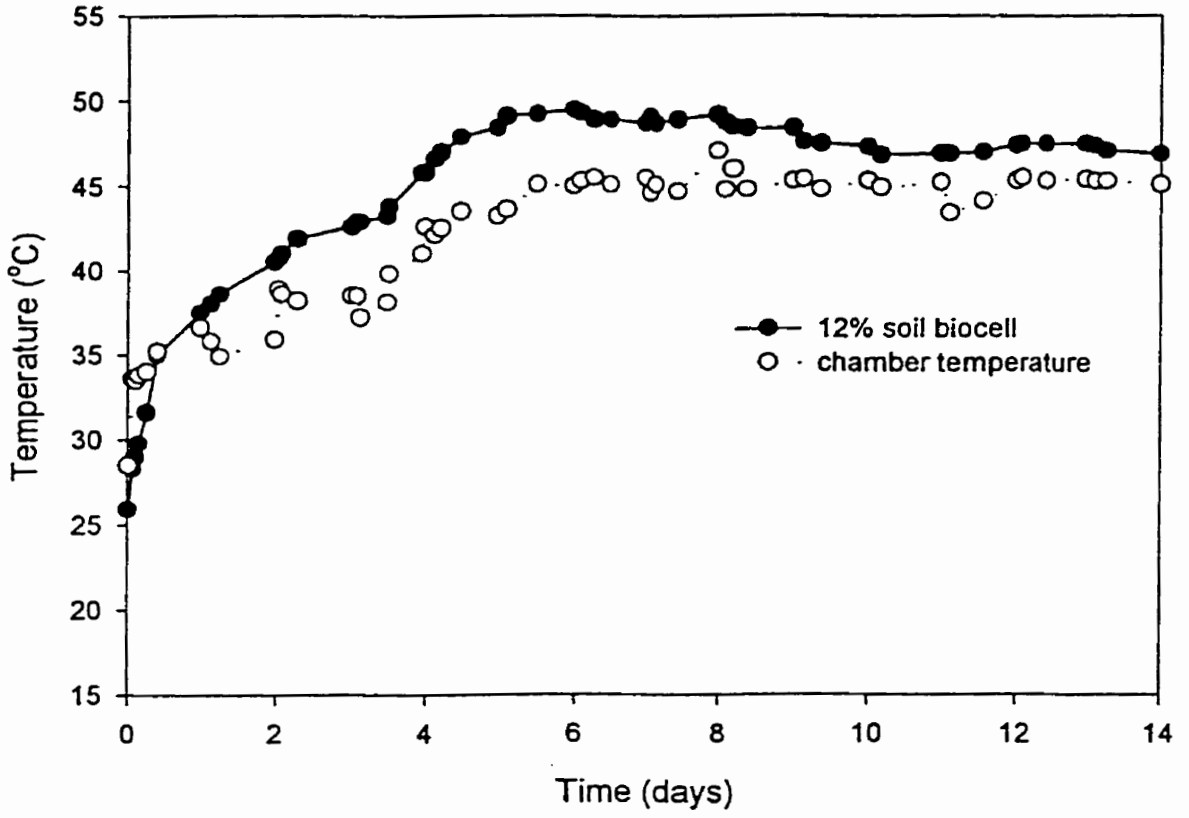
8% soil loading
Temperature Profile



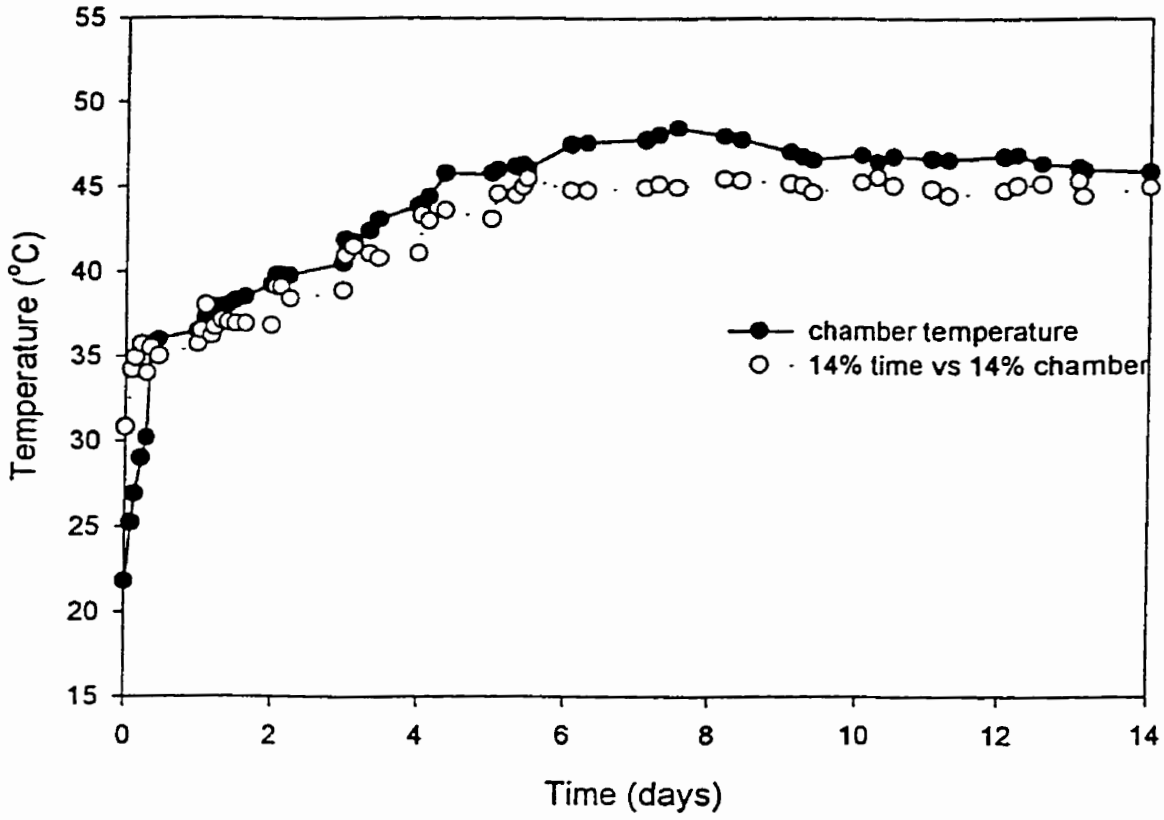
10% soil loading
Temperature Profile



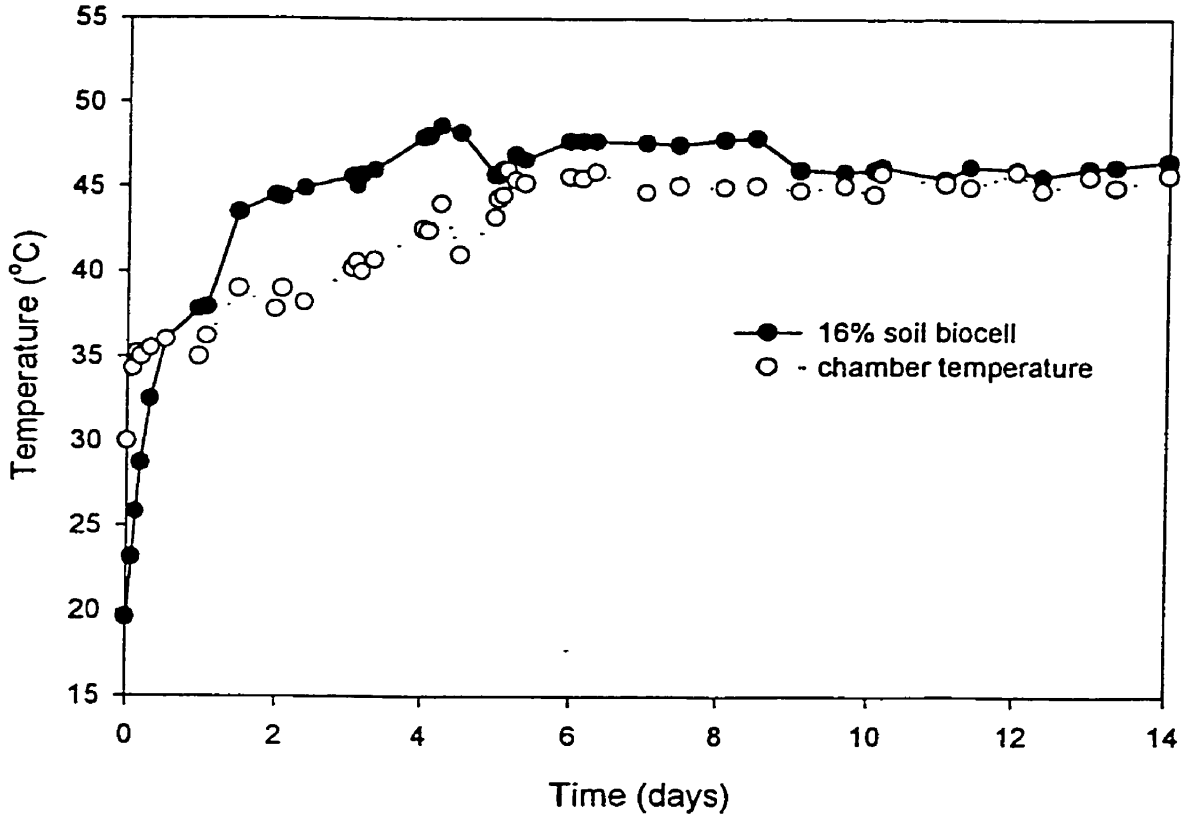
12% soil loading
Temperature Profile



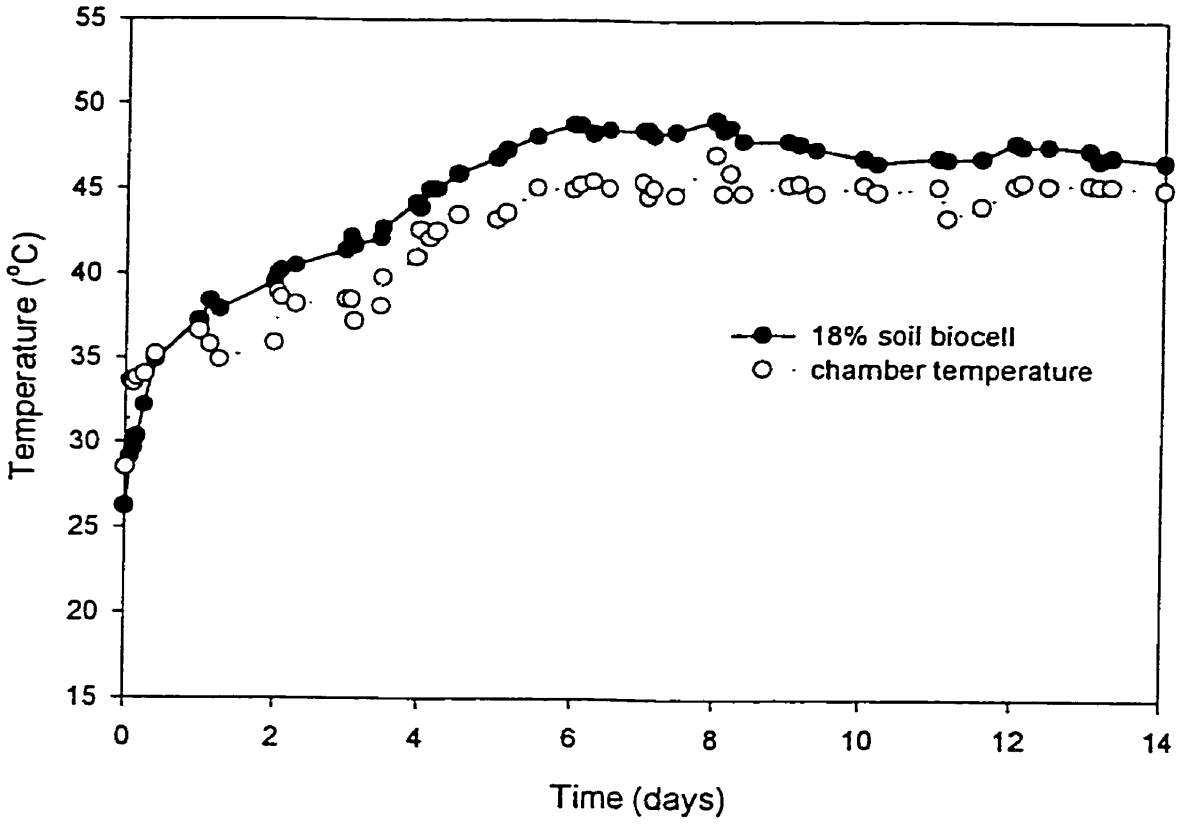
14% soil loading
Temperature Profile



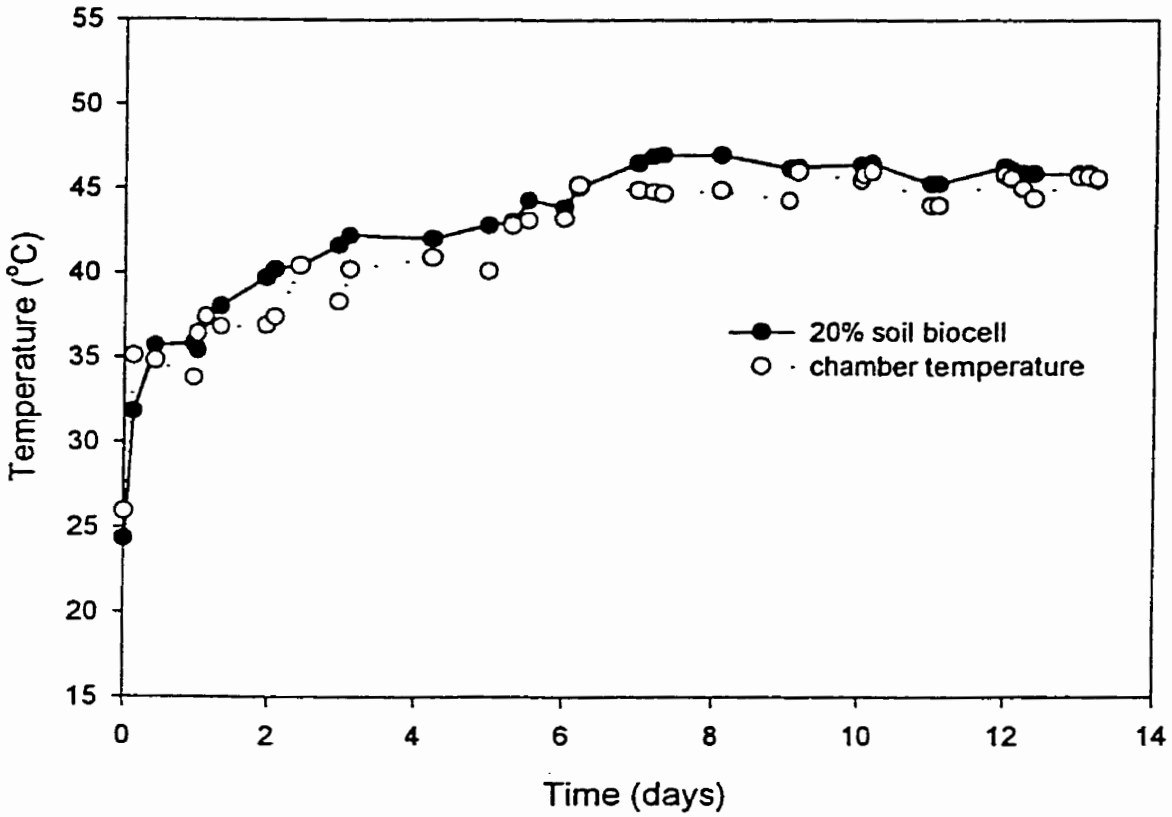
16% soil loading
Temperature Profile



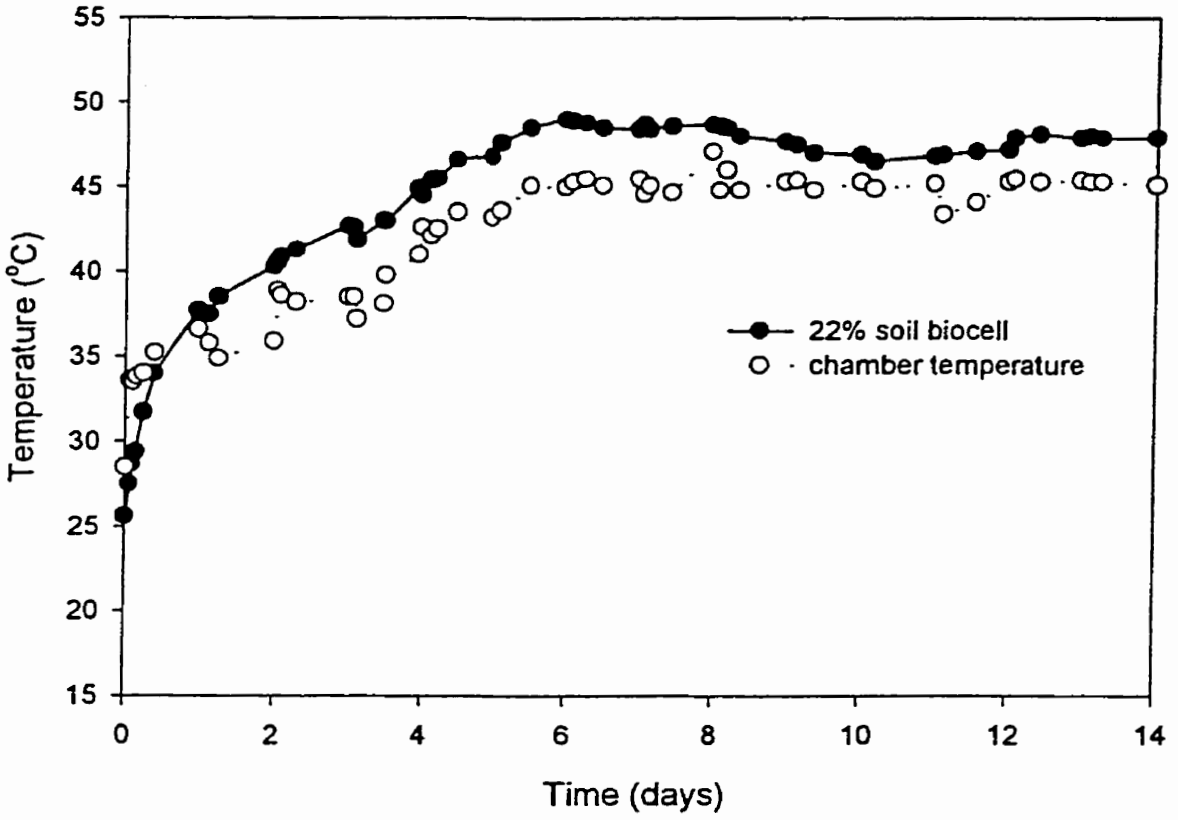
18% soil loading
Temperature Profile



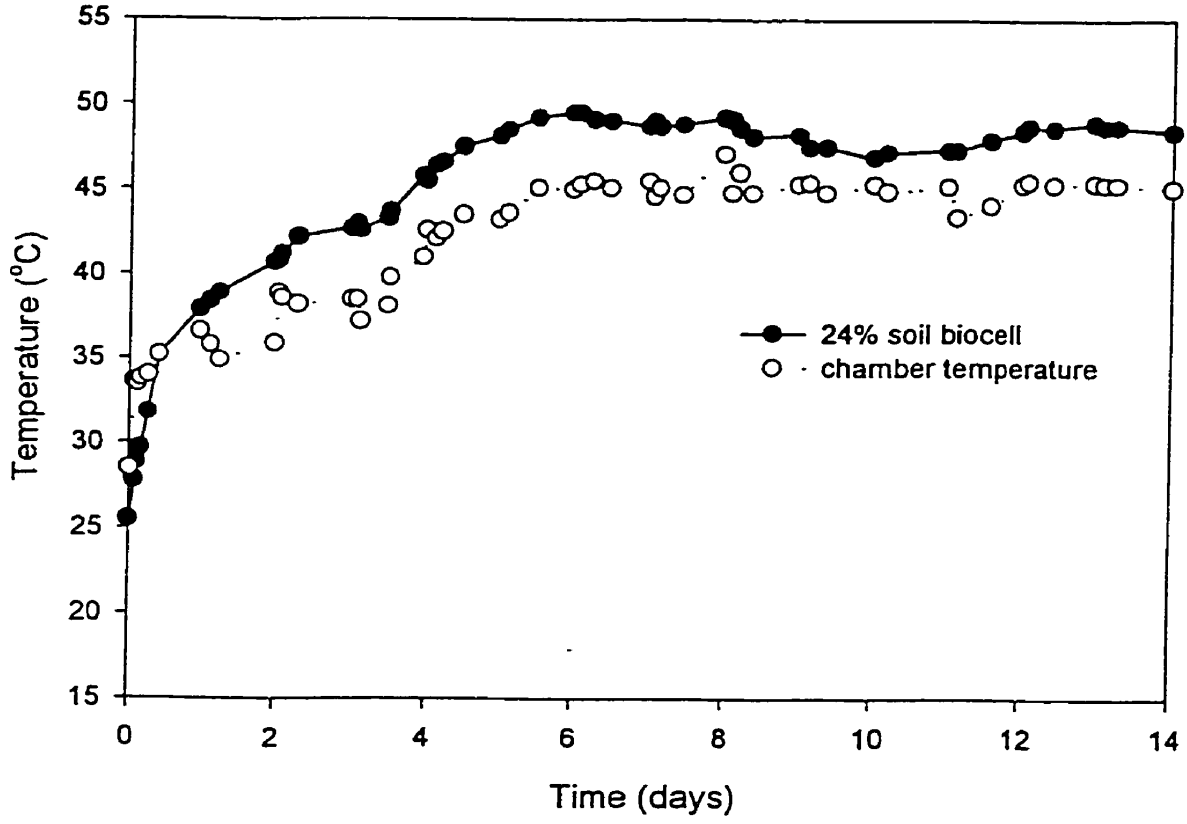
20% soil loading
Temperature Profile



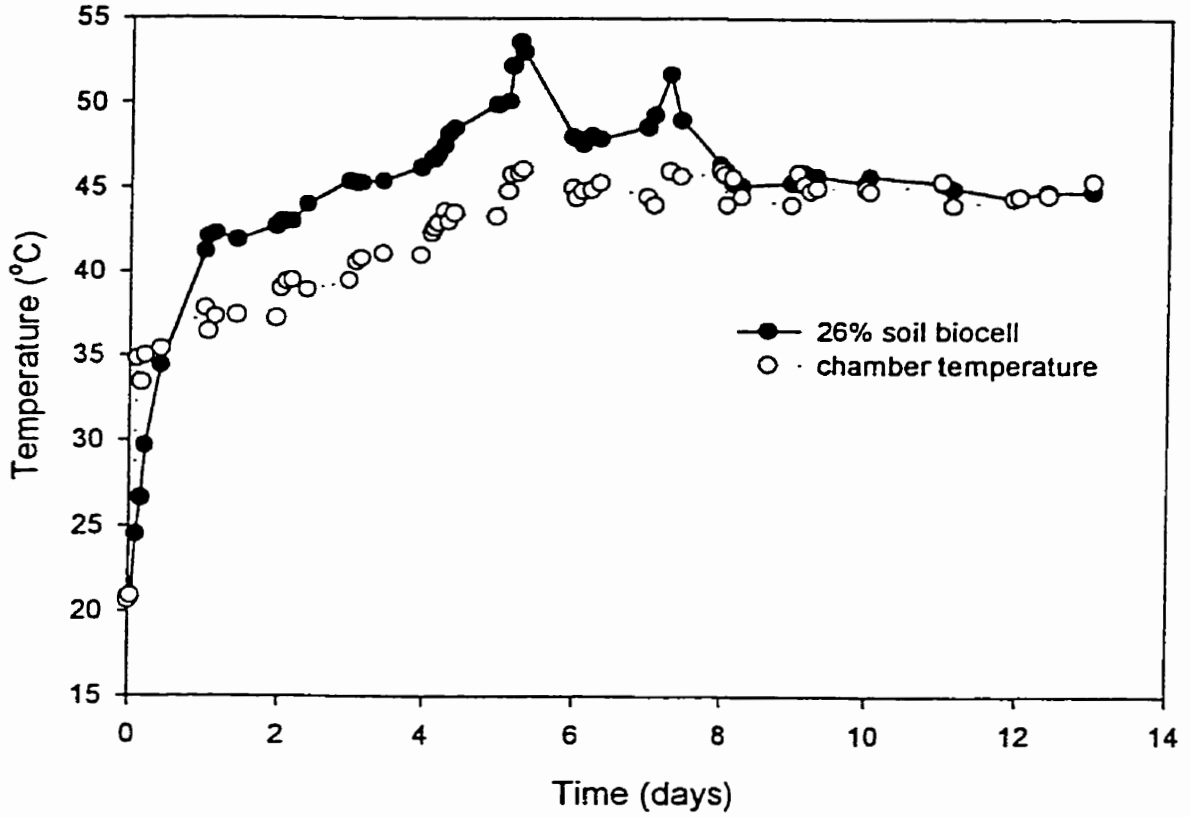
22% soil loading
Temperature Profile



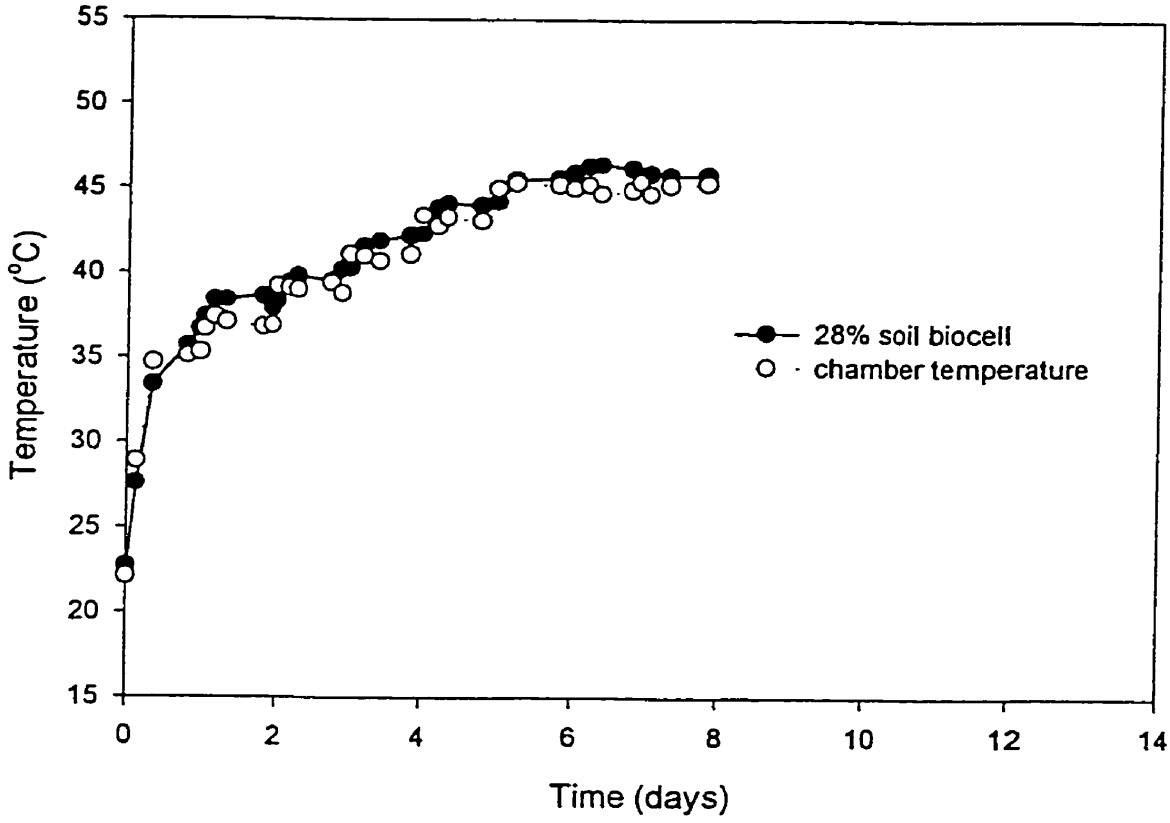
24% soil loading
Temperature Profile



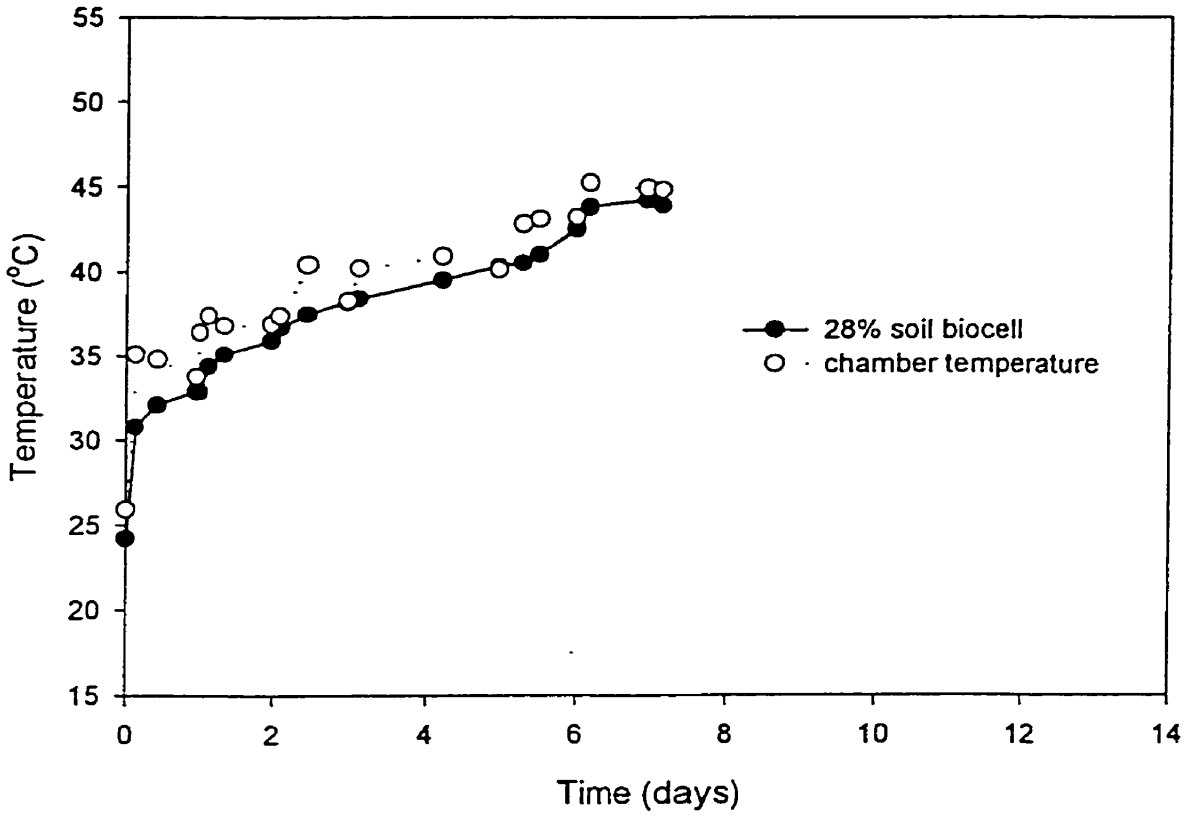
26% soil loading
Temperature Profile



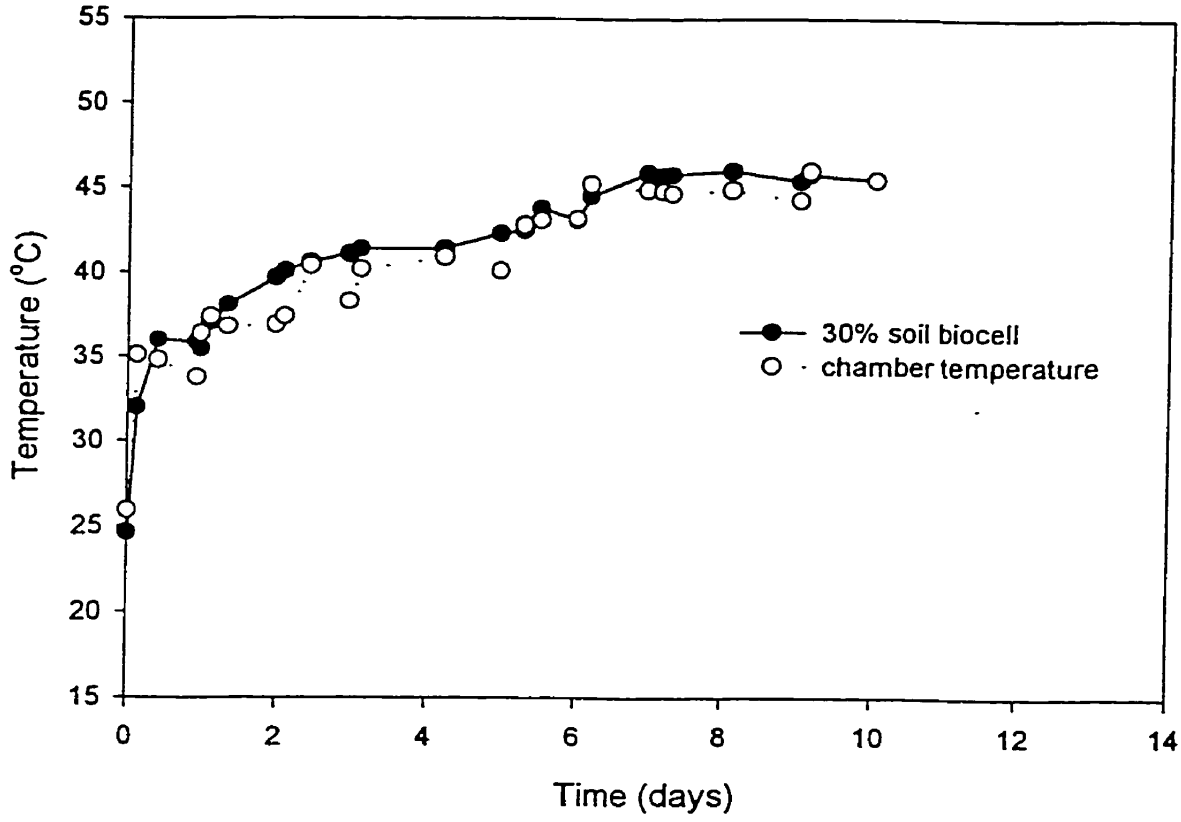
28a% soil loading
Temperature Profile



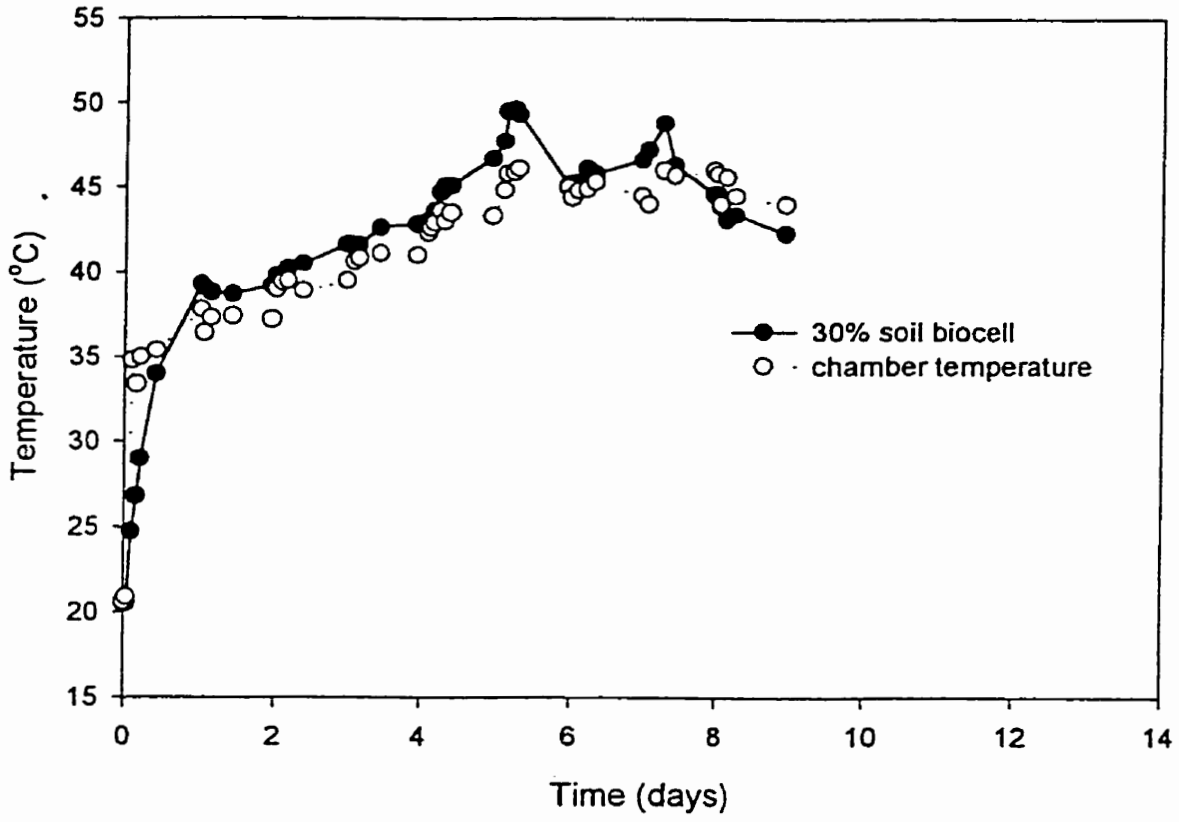
28b% soil loading
Temperature Profile

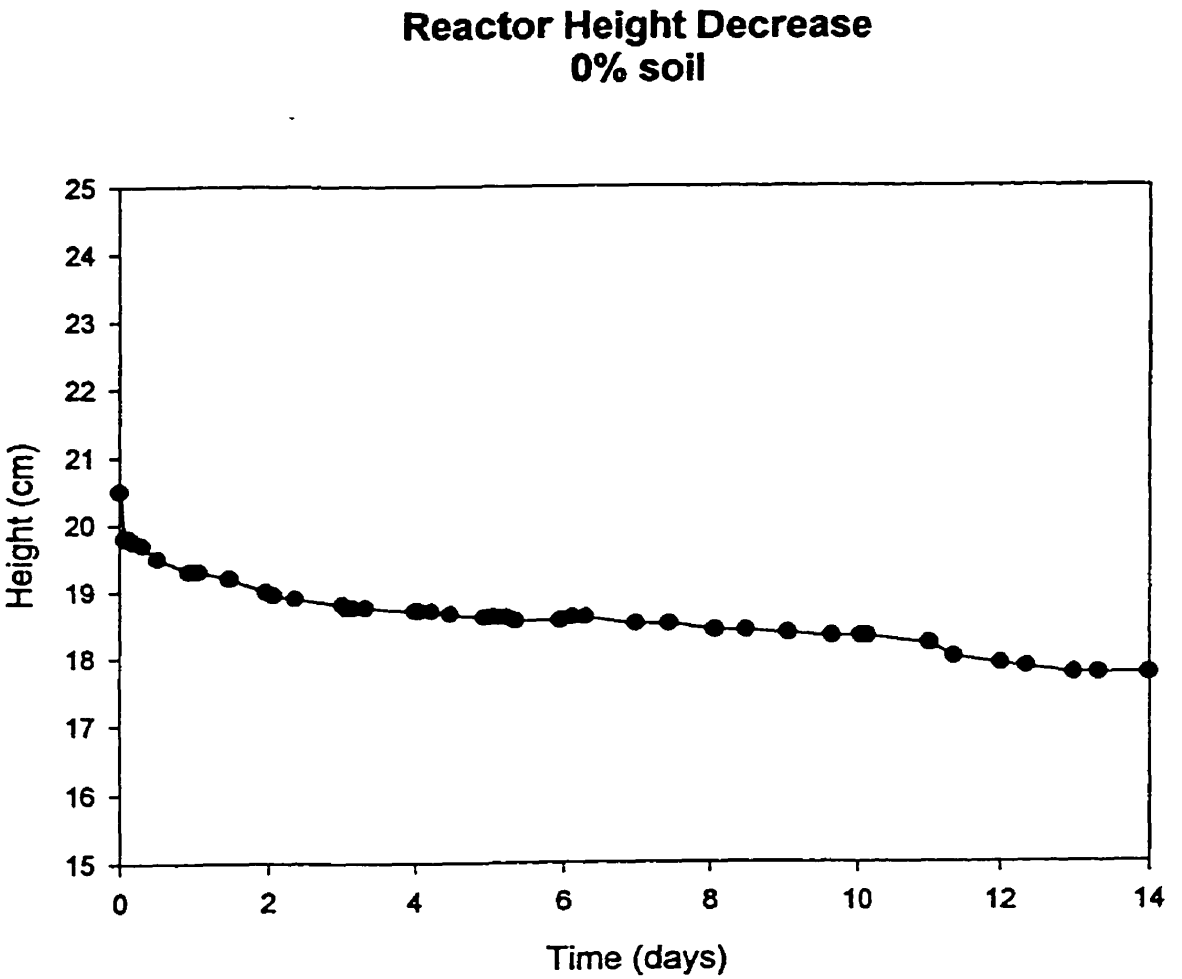


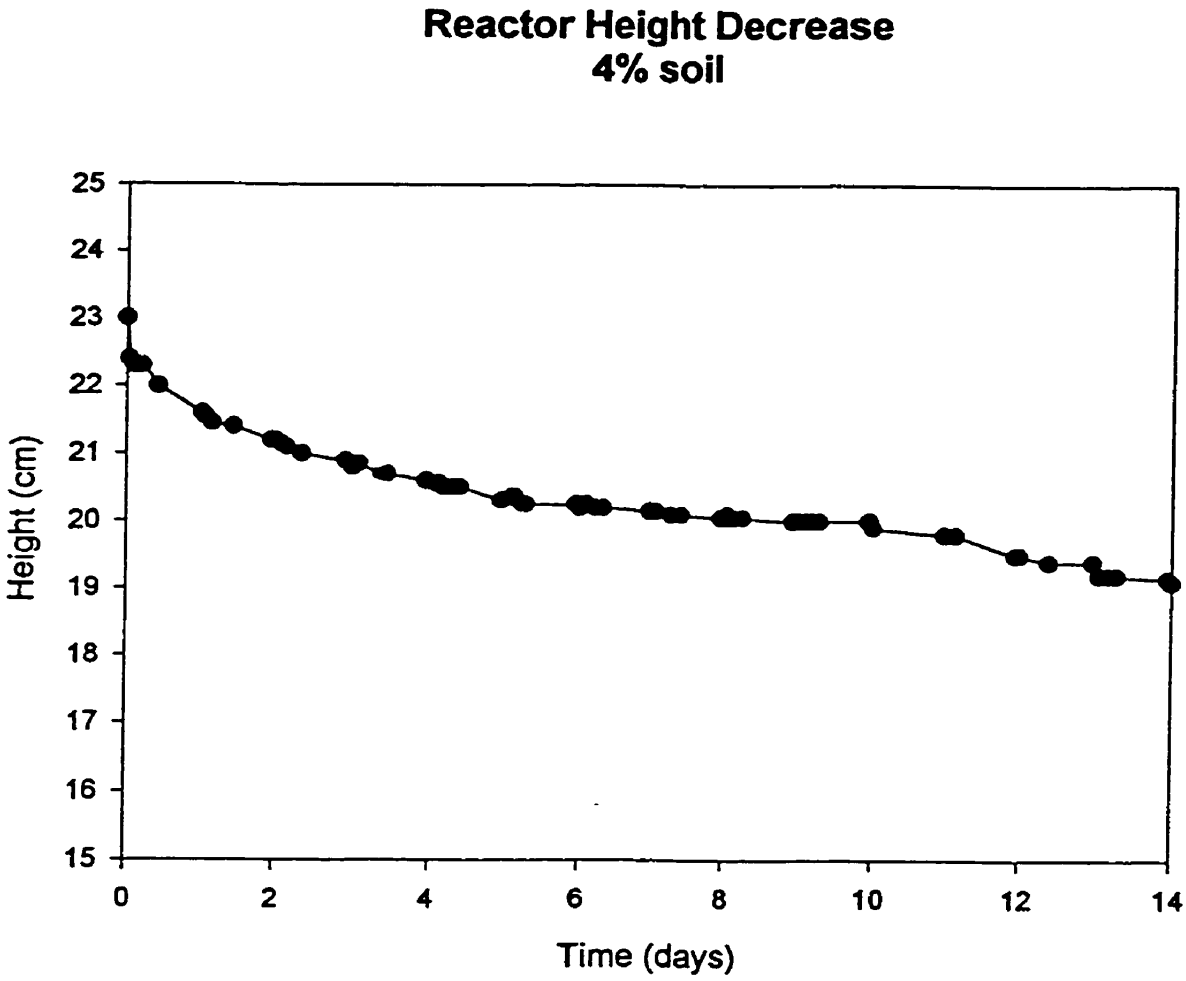
30a% soil loading
Temperature Profile

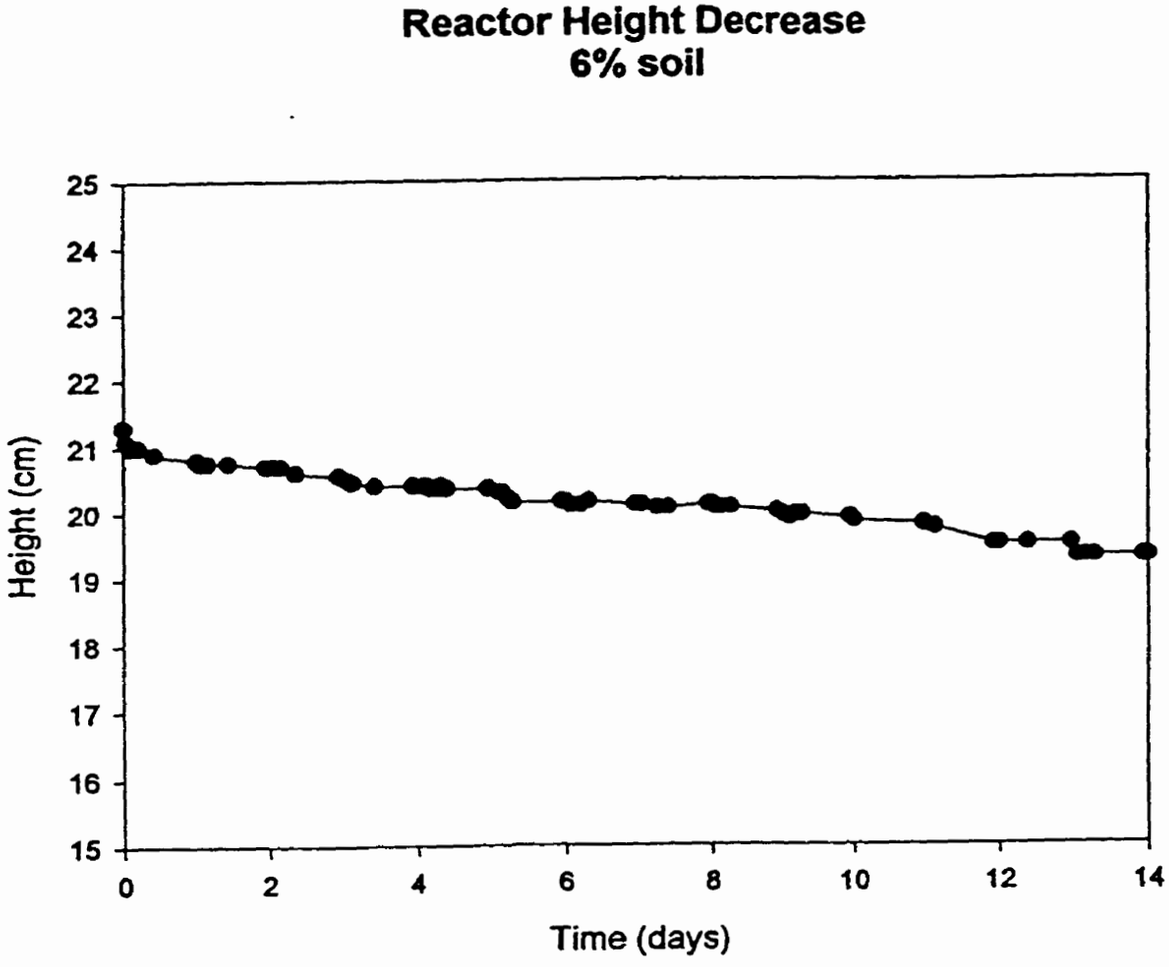


30b% soil loading
Temperature Profile

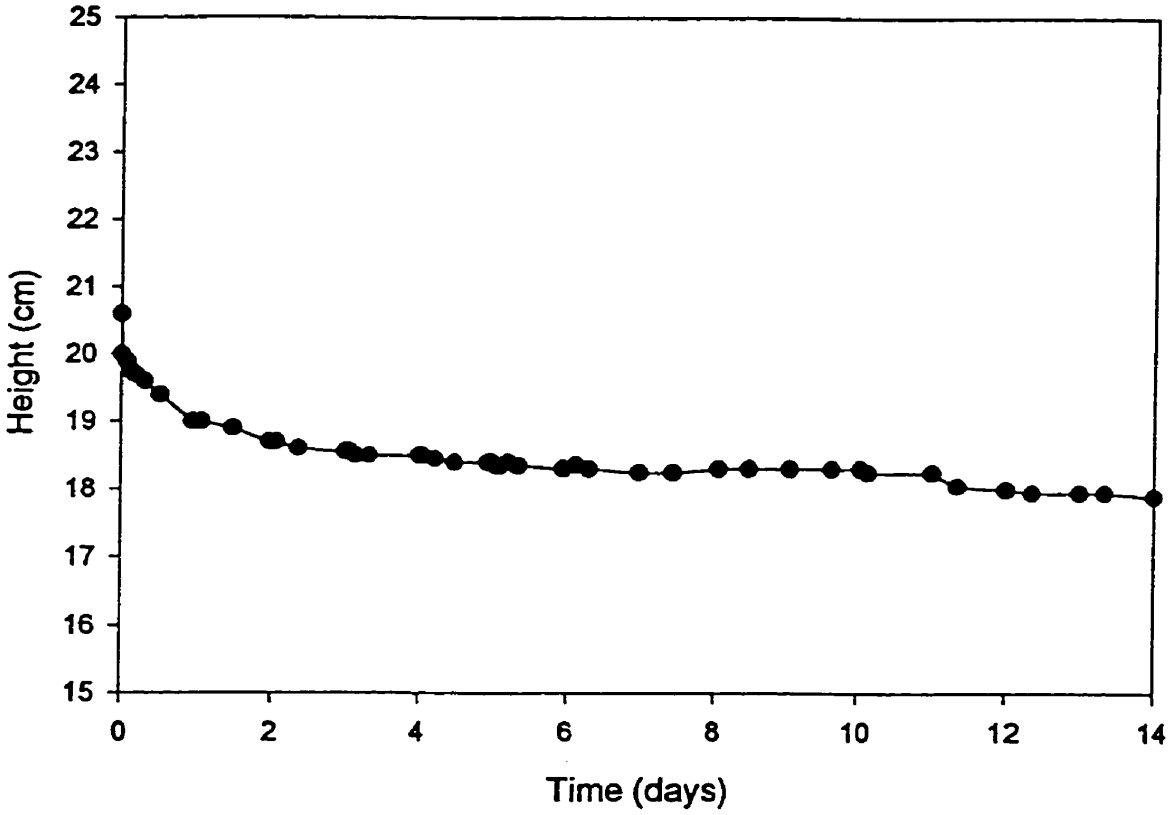


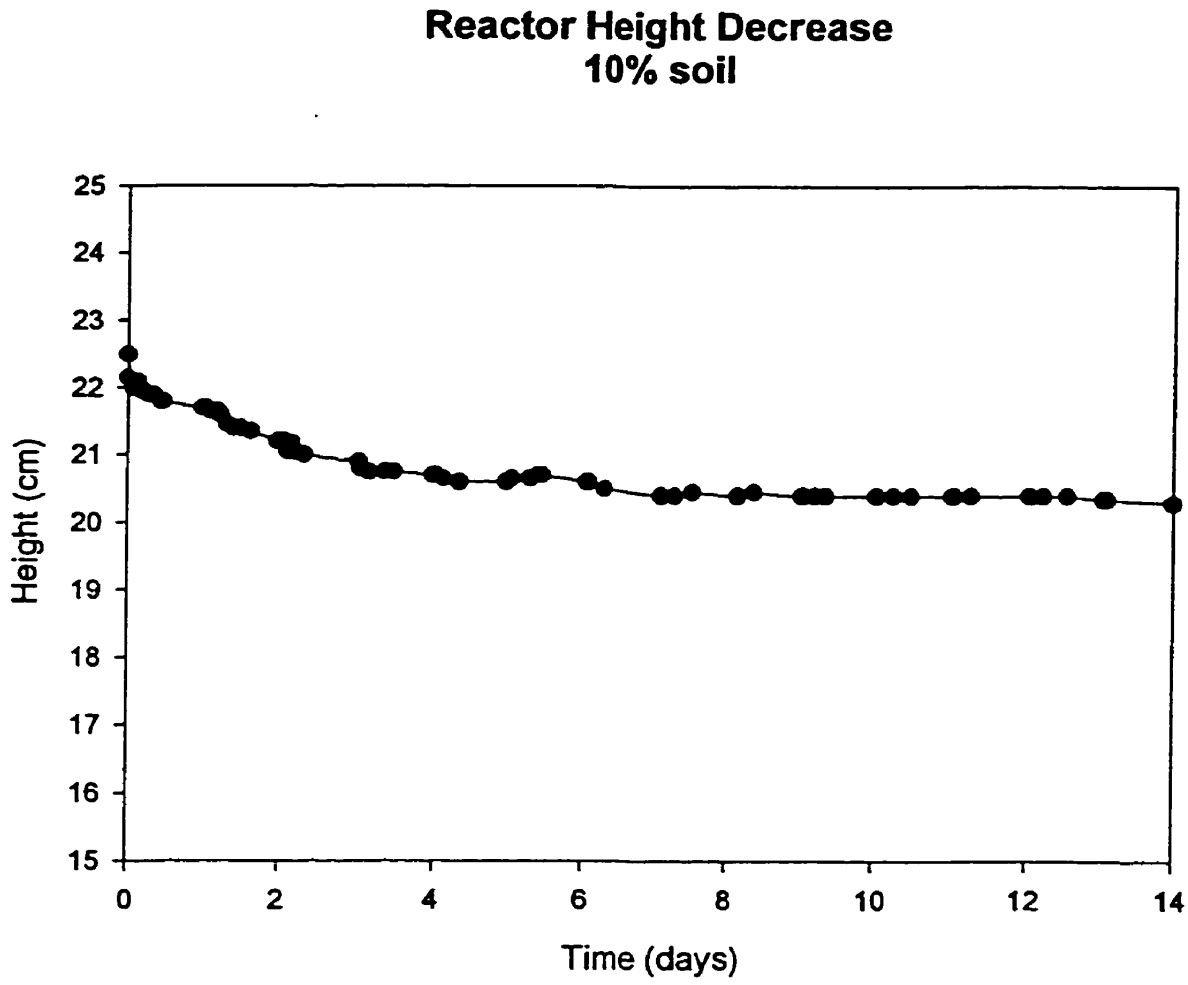

Reactor Height Decrease
0% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)


Reactor Height Decrease
4% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

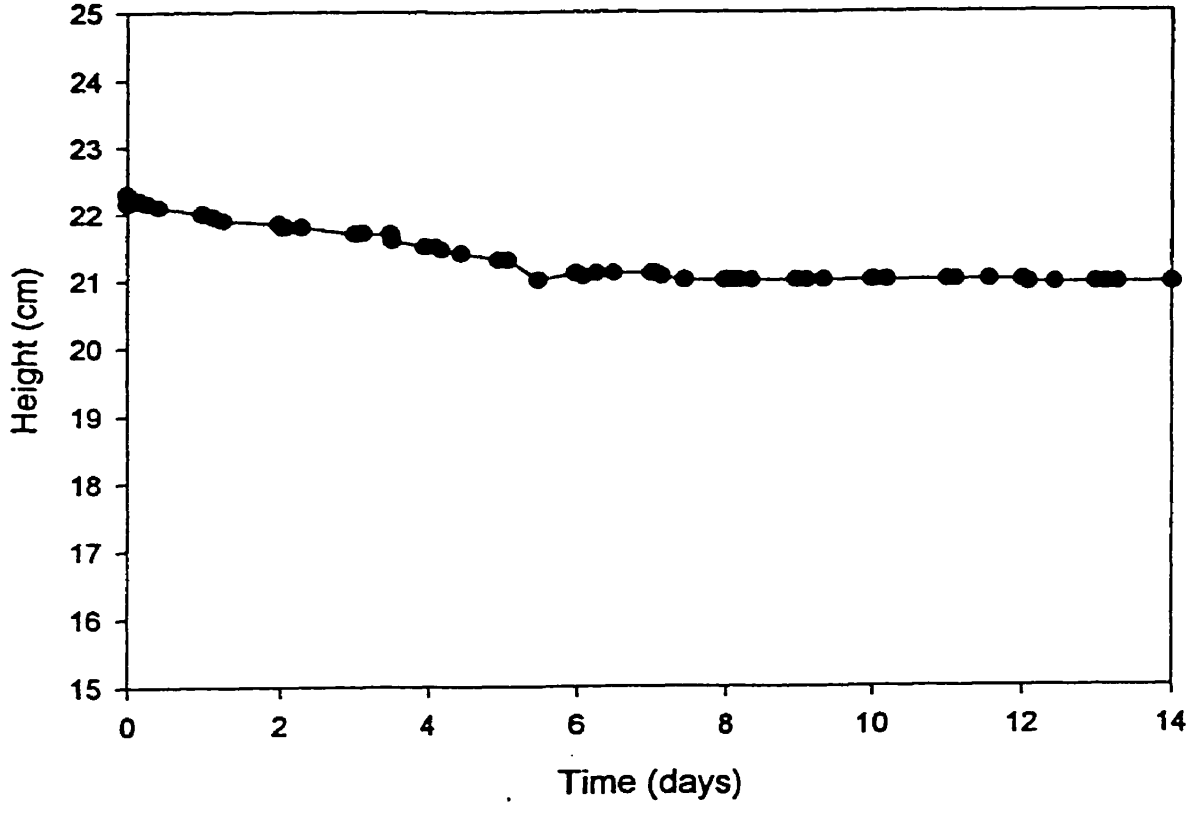

Reactor Height Decrease
6% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

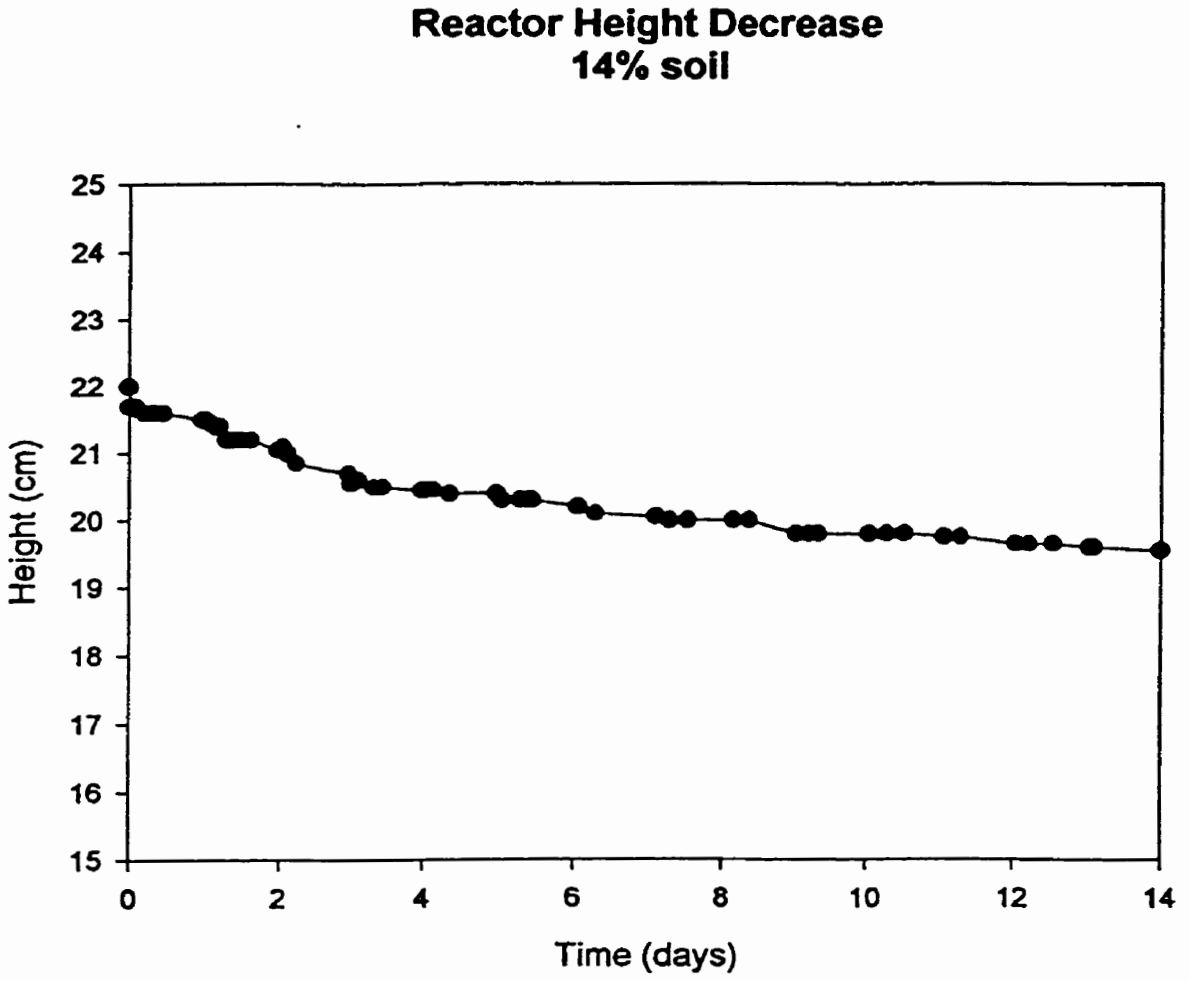
Reactor Height Decrease
8% soil



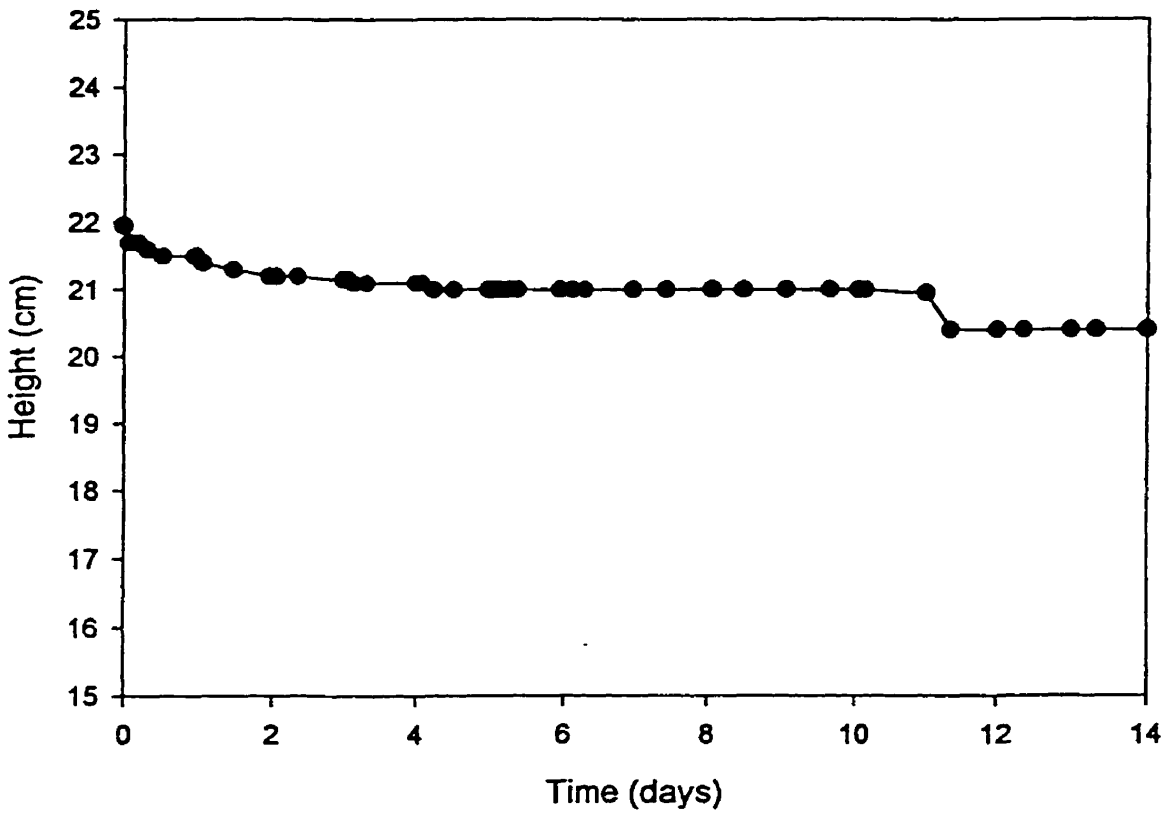

Reactor Height Decrease
10% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

Reactor Height Decrease
12% soil

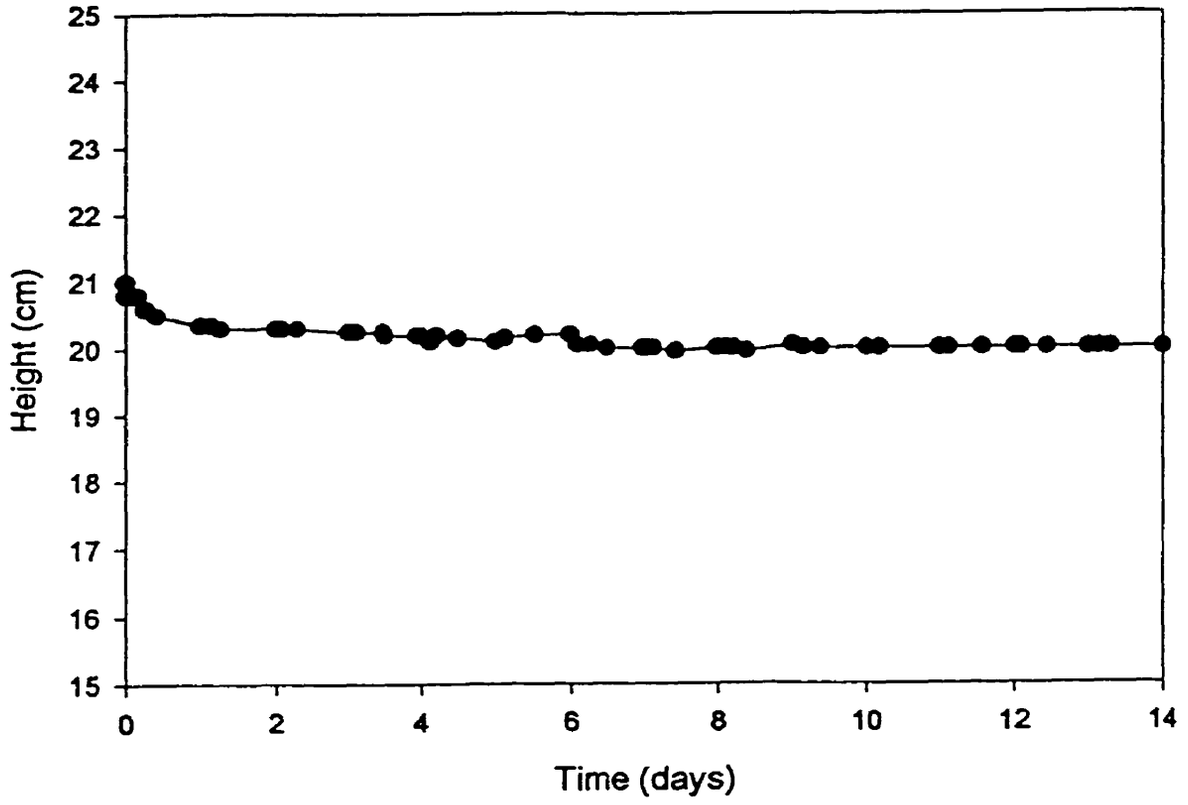


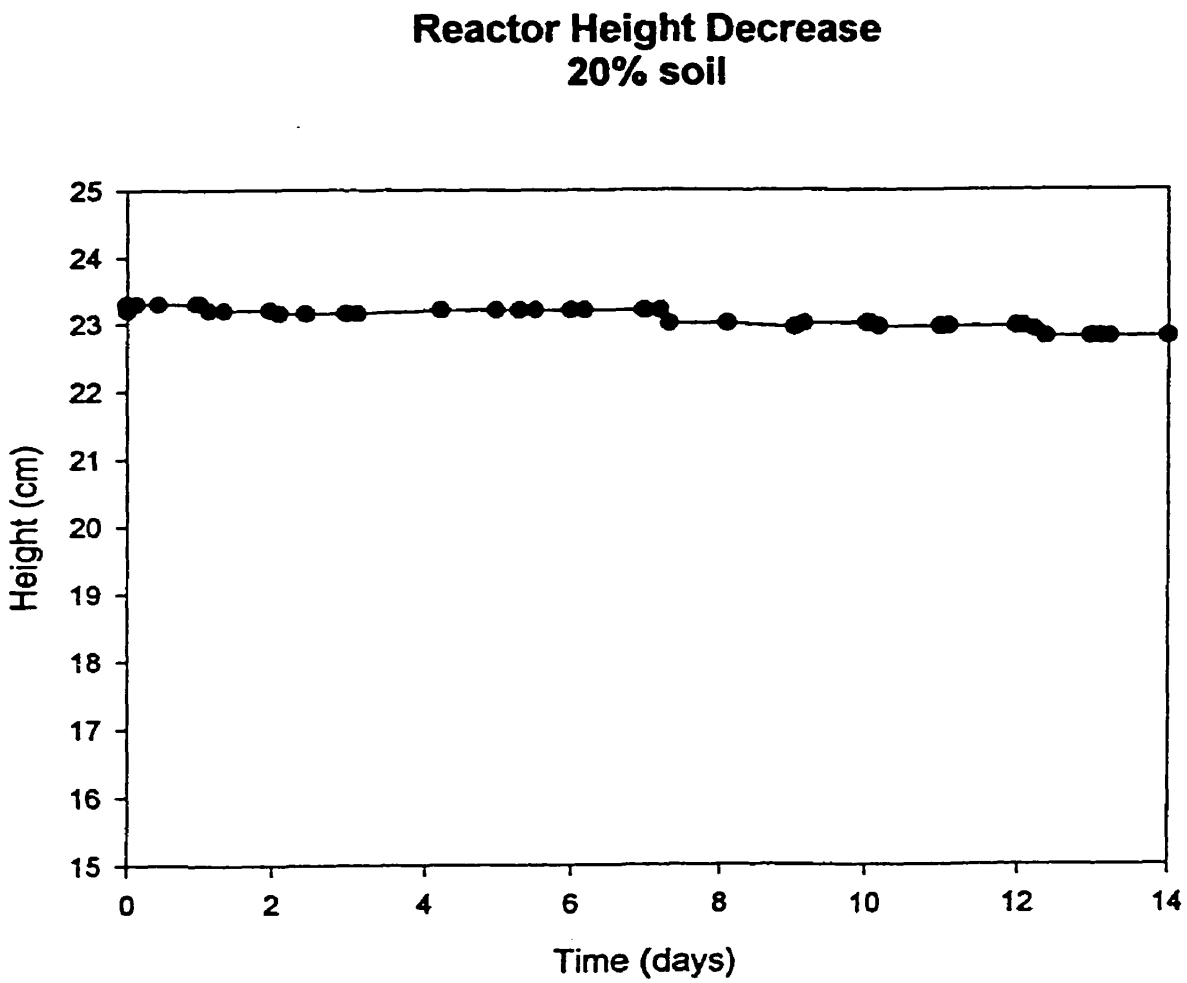

Reactor Height Decrease
14% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

Reactor Height Decrease
16% soil

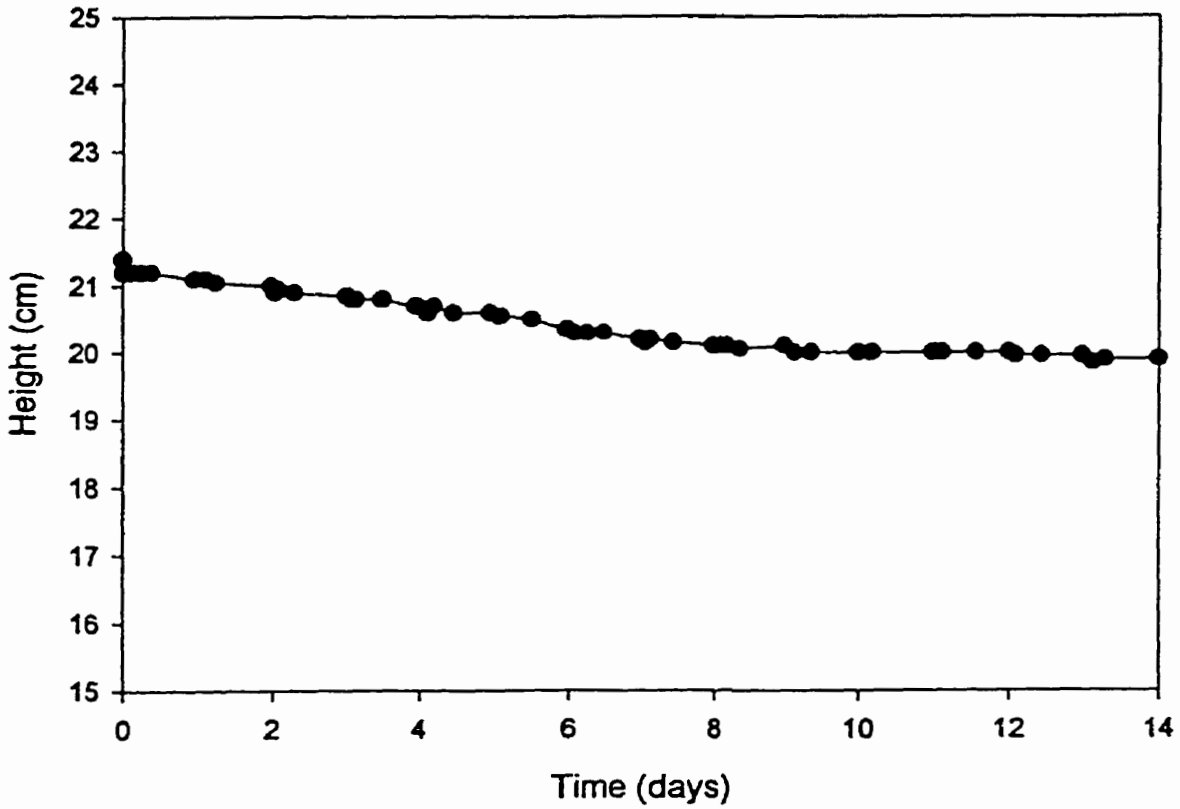


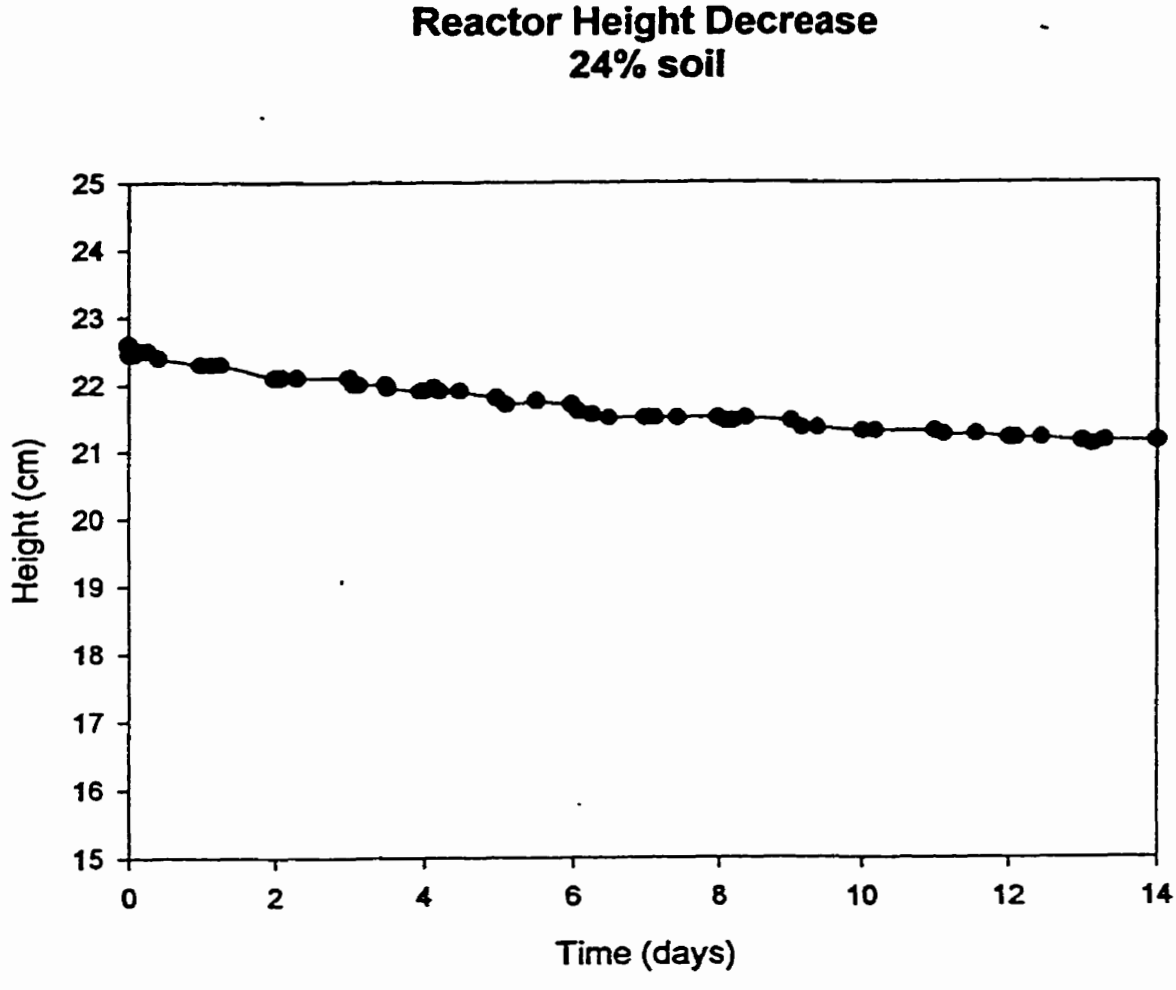
Reactor Height Decrease
18% soil

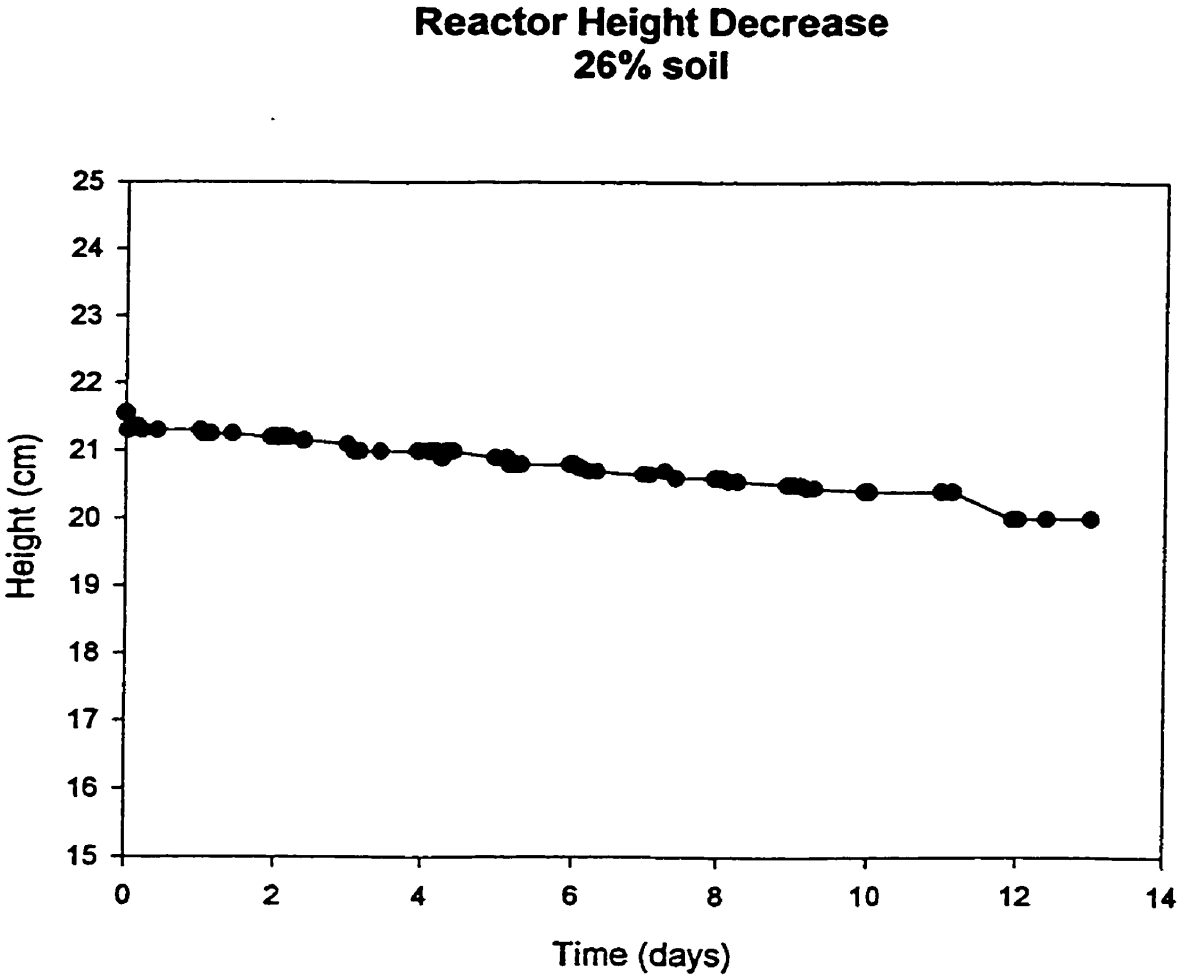


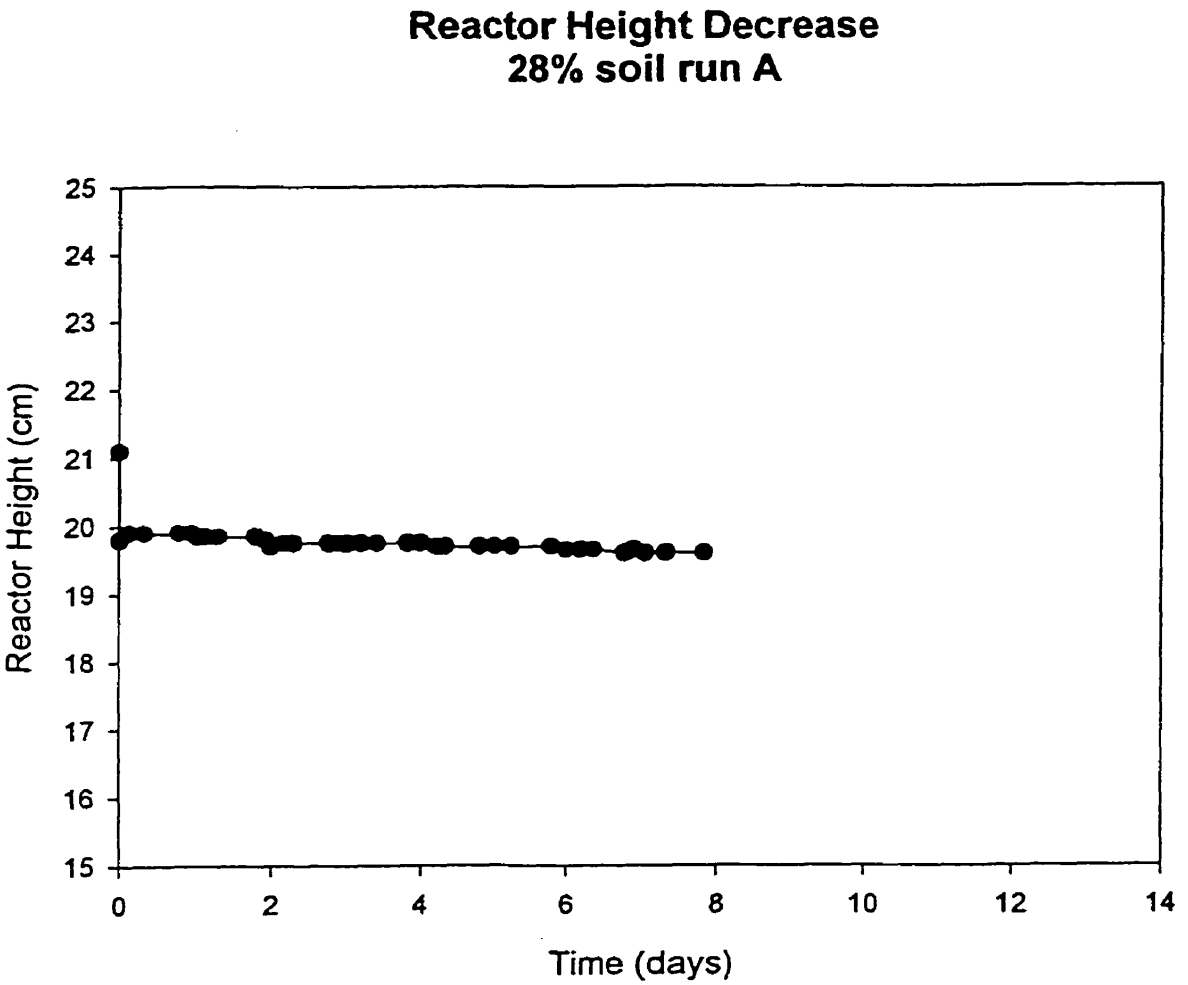

Reactor Height Decrease
20% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

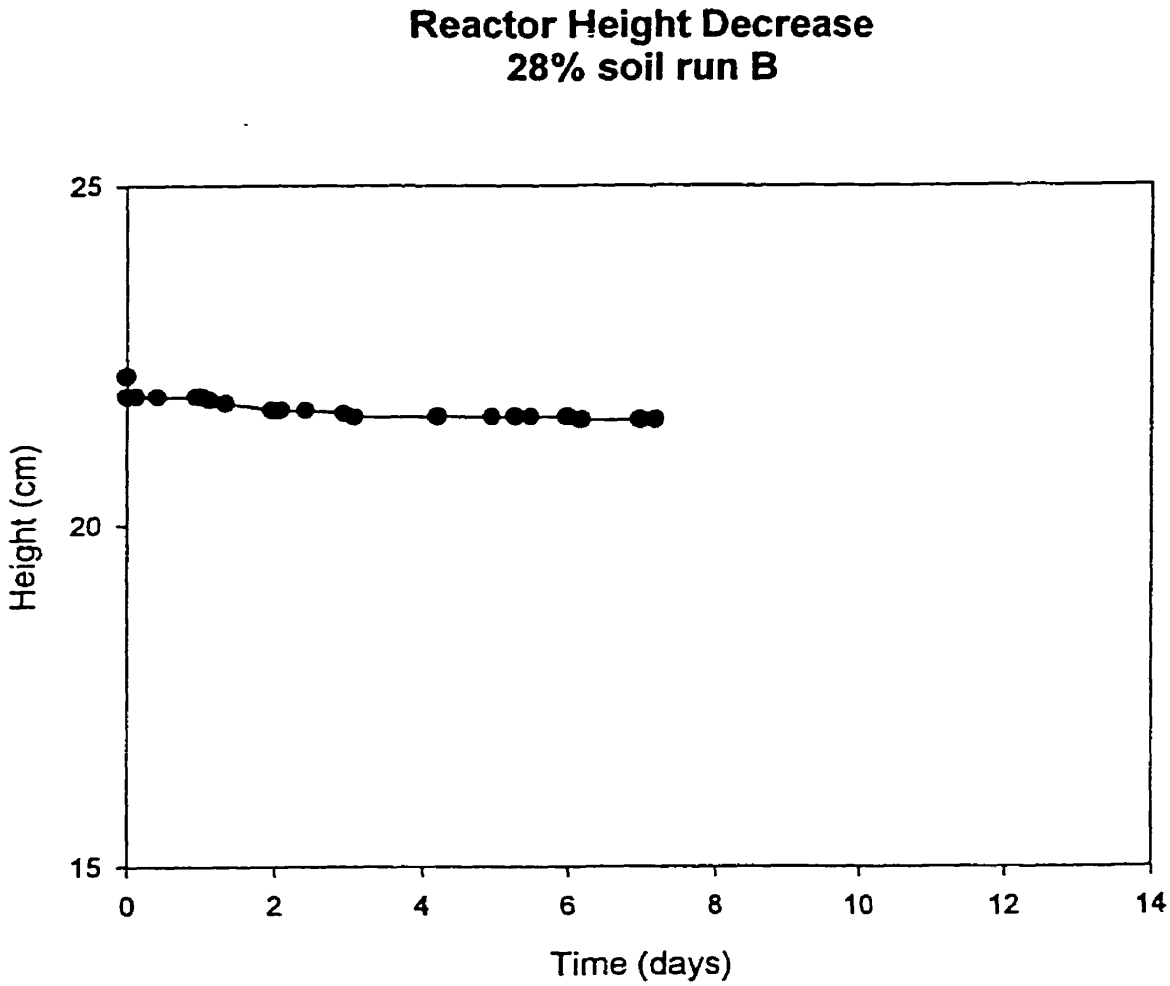
Reactor Height Decrease
22% soil



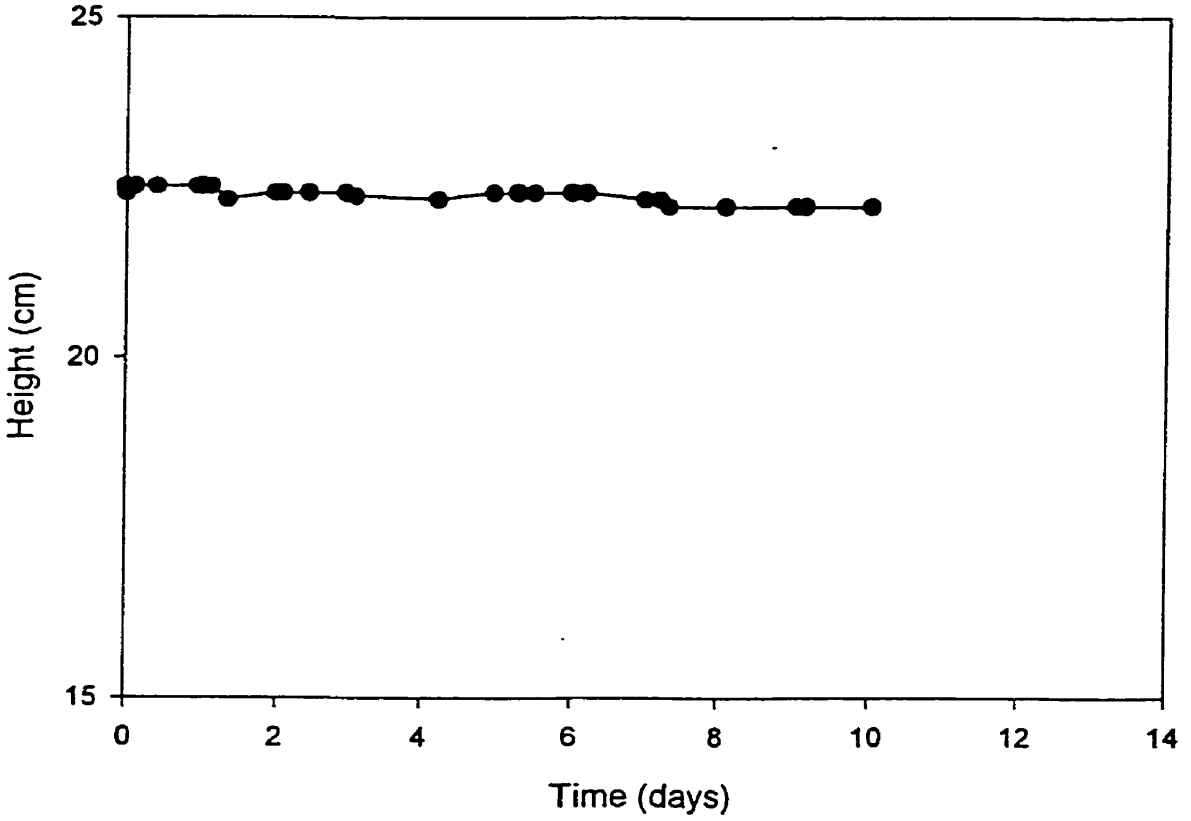

Reactor Height Decrease
24% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)


Reactor Height Decrease
26% soil
Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)

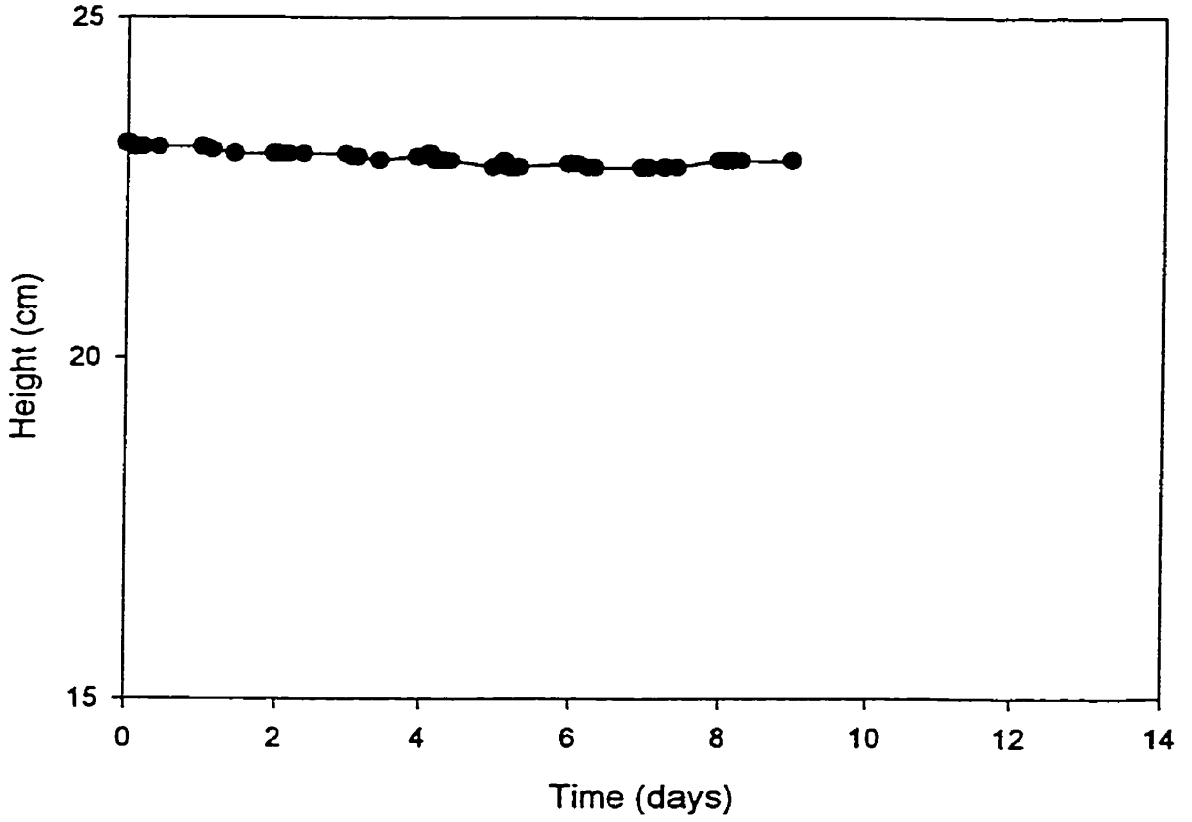

Reactor Height Decrease
28% soil run A
Reactor Height (cm)
25
24
23
22
21
20
19
18
17
16
15
0
2
4
6
8
10
12
14
Time (days)


Reactor Height Decrease
28% soil run B
25
20
15
Height (cm)
0
2
4
6
8
10
12
14
Time (days)

Reactor Height Decrease
30% soil run A



Reactor Height Decrease
30% soil run B



APPENDIX C-3
VOLATILE SOLIDS REDUCTION DATA

VOLATILE SOLIDS DATA

0% soil

Initial Conditions: **Total weight:** **600.00 grams** **VS = 156.1 g**

final reactor ↑ mass

Final compost data:

Soil (%)	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
0	68.2375	82.1693	74.4678	71.8023	7.7015	55.280	44.720	42.783	57.217	23.768	0.56807	0.1087	30.3742
0	91.0246	103.4255	95.9838	93.5602	7.442	60.009	39.991	48.871	51.129	27.150		0.1110	28.8776
0	87.489	96.4165	91.2461	89.6248	5.170	57.915	42.085	43.153	56.847	23.974		0.1032	33.9105
0	70.2894	85.1268	76.7684	73.9234	8.358	56.333	43.667	43.911	56.089	24.395		0.1089	30.2212
					Mean:	57.385	42.615	44.679	55.321	24.822		0.108	30.846
					Std Dev:	1.782	1.782	2.454	2.454	1.363		0.003	1.863
					% rel SD	3.106	4.182	5.492	4.436	5.492		2.694	6.039

initial VS (kg)	0.1561	initial VS (%):	26.0167
final VS (kg)	0.1079	final VS (%):	44.6794
VS_f/VS_i	0.6915		

8-C

VOLATILE SOLIDS DATA

4% soil

Initial Conditions: **Total weight:** **625.083 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
4	66.8303	75.602	70.3875	68.2195	5.2145	59.447	40.553	60.947	39.053	33.859	0.51631	0.1276	18.2509
4	87.0997	99.3823	91.964	88.8948	7.4183	60.397	39.603	63.096	36.904	35.054		0.1290	17.3501
4	85.6884	96.3883	90.1794	87.5401	6.2089	58.028	41.972	58.769	41.231	32.649		0.1274	18.4138
4	92.0896	107.0174	98.0442	94.3195	8.9732	60.111	39.889	62.552	37.448	34.751		0.1288	17.4717
					Mean:	59.495	40.505	61.341	38.659	34.078		0.128	17.872
					Std Dev:	0.915	0.915	1.682	1.682	0.935		0.001	0.466
					% rel SD	1.538	2.259	2.742	4.351	2.742		0.568	2.609

initial VS (kg)	0.1561	initial VS (%):	24.973
final VS (kg)	0.128	final VS (%):	61.341
VS_f/VS_i	0.82		

8-7

VOLATILE SOLIDS DATA

6% soil

Initial Conditions: **Total weight:** **638.428 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
6	84.091	97.8239	90.1116	86.8517	7.7123	56.159	43.841	54.146	45.854	30.081	0.52591	0.1248	20.0257
6	104.007	109.5463	106.372	105.1181	3.175	57.311	42.689	53.020	46.980	29.455		0.1190	23.7459
6	90.1362	97.0009	93.1011	91.5361	3.900	56.809	43.191	52.784	47.216	29.325		0.1199	23.1929
6	103.901	108.8821	105.941	104.7851	2.941	59.042	40.958	56.661	43.339	31.478		0.1220	21.8134
					Mean:	57.330	42.670	54.153	45.847	30.085		0.121	22.194
					Std Dev:	1.069	1.069	1.537	1.537	0.854		0.002	1.436
					% rel SD	1.865	2.506	2.838	3.352	2.838		1.846	6.472

initial VS (kg)	0.1561	initial VS (%):	24.451
final VS (kg)	0.1214544	final VS (%):	54.153
VS_f/VS_i	0.7780552		

VOLATILE SOLIDS DATA

8% soil

Initial Conditions: **Total weight:** **652.344 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
8	89.871	98.4312	94.8512	93.2287	3.58	41.821	58.179	32.579	67.421	18.099	0.5475	0.1038	33.5214
8	103.891	109.8768	107.322	106.2163	2.5553	42.692	57.308	32.221	67.779	17.900		0.1011	35.2367
8	86.7645	94.1531	91.1584	89.9076	2.9947	40.531	59.469	28.467	71.533	15.815		0.0927	40.6245
8	90.1123	98.1447	94.5295	93.0178	3.6152	45.008	54.992	34.223	65.777	19.013		0.1030	33.9913
					Mean:	42.513	57.487	31.872	68.128	17.707		0.100	35.843
					Std Dev:	1.633	1.633	2.106	2.106	1.170		0.004	2.831
					% rel SD	3.840	2.840	6.608	3.092	6.608		4.412	7.897

initial VS (kg)	0.1561	initial VS (%):	23.929
final VS (kg)	0.10015	final VS (%):	31.872
VS_f/VS_i	0.64157		

C-83

VOLATILE SOLIDS DATA

10% soil

Initial Conditions: **Total weight:** **666.882 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
10	78.9491	90.1263	84.7411	82.6756	5.3852	48.180	51.820	35.661	64.339	19.812	0.56784	0.1049	32.7774
10	82.3495	91.2781	87.1207	85.5023	4.1574	46.563	53.437	33.920	66.080	18.845		0.1029	34.0635
10	87.1237	101.2322	94.3158	91.5845	6.9164	49.023	50.977	37.976	62.024	21.098		0.1099	29.5775
10	91.752	104.7849	97.8823	95.4218	6.9026	52.963	47.037	40.137	59.863	22.298		0.1072	31.3239
					Mean:	49.182	50.818	36.924	63.076	20.513		0.106	31.936
					Std Dev:	2.355	2.355	2.348	2.348	1.304		0.003	1.671
					% rel SD	4.788	4.634	6.358	3.722	6.358		2.455	5.233

initial VS (kg)	0.1561	initial VS (%):	23.407
final VS (kg)	0.106	final VS (%):	36.924
VS_f/VS_i	0.67905		

VOLATILE SOLIDS DATA

12% soil

Initial Conditions: **Total weight:** **682.093 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
12	76.1589	88.6843	81.4984	79.3218	7.1859	57.371	42.629	40.764	59.236	22.647	0.59159	0.1028	34.1425
12	89.2897	103.8791	95.3671	92.7994	8.512	58.344	41.656	42.250	57.750	23.472		0.1041	33.3002
12	97.9651	105.108	100.873	99.6814	4.235	59.292	40.708	40.974	59.026	22.763		0.0987	36.7878
12	91.6075	106.8928	98.4867	95.8759	8.406	54.995	45.005	37.952	62.048	21.084		0.1010	35.2682
					Mean:	57.500	42.500	40.485	59.515	22.492		0.102	34.875
					Std Dev:	1.598	1.598	1.569	1.569	0.872		0.002	1.307
					% rel SD	2.780	3.761	3.876	2.636	3.876		2.006	3.747

initial VS (kg)	0.1561	initial VS (%):	22.885
final VS (kg)	0.10166	final VS (%):	40.485
VS_f/VS_i	0.65125		

C-85

VOLATILE SOLIDS DATA

14% soil

Initial Conditions: **Total weight:** **698.006 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
14	92.0314	104.1803	97.7853	95.6921	6.395	52.639	47.361	36.379	63.621	20.210	0.60982	0.1051	32.6911
14	74.0182	83.5936	78.0389	76.4636	5.5547	58.010	41.990	39.180	60.820	21.767		0.1003	35.7305
14	76.9185	90.4875	83.3512	81.201	7.1363	52.593	47.407	33.426	66.574	18.570		0.0966	38.0944
14	80.1894	92.8234	86.6371	84.5613	6.1863	48.965	51.035	32.194	67.806	17.886		0.1002	35.8135
					Mean:	53.052	46.948	35.295	64.705	19.608		0.101	35.582
					Std Dev:	3.227	3.227	2.710	2.710	1.505		0.003	1.920
					% rel SD	6.083	6.874	7.678	4.188	7.678		2.981	5.396

initial VS (kg)	0.1561	initial VS (%):	22.364
final VS (kg)	0.10056	final VS (%):	35.295
VS_f/VS_i	0.64418		

C-86

VOLATILE SOLIDS DATA

16% soil

Initial Conditions: **Total weight:** **714.681 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
16	84.0218	96.0816	89.7819	87.8199	6.2997	52.237	47.763	34.062	65.938	18.923	0.62153	0.1011	35.2234
16	77.9842	84.1896	80.7652	79.7137	3.424	55.184	44.816	37.810	62.190	21.006		0.1053	32.5319
16	79.8162	92.8431	85.9561	83.7261	6.887	52.868	47.132	36.320	63.680	20.178		0.1064	31.8410
16	65.1896	78.4981	70.8328	68.4833	7.665	57.597	42.403	41.634	58.366	23.130		0.1097	29.7081
					Mean:	54.471	45.529	37.457	62.543	20.809		0.106	32.326
					Std Dev:	2.112	2.112	2.757	2.757	1.531		0.003	1.970
					% rel SD	3.877	4.639	7.359	4.407	7.359		2.911	6.095

initial VS (kg)	0.1561	initial VS (%):	21.842
final VS (kg)	0.10564	final VS (%):	37.457
VS_f/VS_i	0.67674		

VOLATILE SOLIDS DATA

18% soil

Initial Conditions: **Total weight:** 732.139 grams VS = 156.1 g

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
18	87.3174	96.3592	91.5776	89.9749	4.7816	52.883	47.117	37.620	62.380	20.900	0.6105	0.1082	30.6766
18	103.9	109.6997	106.718	105.6702	2.982	51.419	48.581	37.170	62.830	20.650		0.1102	29.3779
18	84.0891	97.0949	90.2359	87.8841	6.859	52.738	47.262	38.261	61.739	21.256		0.1104	29.2794
18	104.006	109.1181	106.531	105.6342	2.587	50.611	49.389	35.512	64.488	19.729		0.1071	31.4066
					Mean:	51.913	48.087	37.141	62.859	20.634		0.109	30.185
					Std Dev:	0.943	0.943	1.017	1.017	0.565		0.001	0.895
					% rel SD	1.817	1.962	2.739	1.618	2.739		1.282	2.966

initial VS (kg)	0.1561	initial VS (%):	21.321
final VS (kg)	0.10898	final VS (%):	37.141
VS_f/VS_i	0.69815		

88-7

VOLATILE SOLIDS DATA

20% soil

Initial Conditions: **Total weight:** **750.5 grams** **VS = 156.1 g**

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
20	90.4461	101.8838	95.0812	92.5708	6.8026	59.475	40.525	54.161	45.839	30.089	0.5834	0.1280	17.9709
20	83.7933	100.0053	90.3882	86.7502	9.6171	59.321	40.679	55.164	44.836	30.647		0.1309	16.1333
20	90.5986	107.3011	96.9364	93.1887	10.3647	62.055	37.945	59.133	40.867	32.851		0.1309	16.1416
20	91.287	104.3945	96.6434	93.7825	7.7511	59.135	40.865	53.411	46.589	29.673		0.1273	18.4270
					Mean:	59.996	40.004	55.467	44.533	30.815		0.129	17.168
					Std Dev:	1.194	1.194	2.206	2.206	1.225		0.002	1.043
					% rel SD	1.991	2.986	3.977	4.953	3.977		1.260	6.077

initial VS (kg)	0.1561	initial VS (%):	20.799
final VS (kg)	0.1293	final VS (%):	55.467
VS_f/VS_i	0.82832		

C-89

VOLATILE SOLIDS DATA

22% soil

Initial Conditions: **Total weight:** 769.764 grams VS = 156.1 g

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
22	90.1353	109.9913	98.7107	95.2643	11.2806	56.812	43.188	40.189	59.811	22.327	0.6681	0.1160	25.7131
22	100.628	115.4321	107.169	*broke	8.263	55.819	44.181	-	-	-		-	-
22	85.6921	108.7518	95.9241	91.8794	12.828	55.628	44.372	39.530	60.470	21.961		0.1172	24.9292
22	95.198	117.9986	105.31	101.3212	12.688	55.649	44.351	39.448	60.552	21.916		0.1169	25.1198
					Mean:	55.977	44.023	39.722	60.278	22.068		0.117	25.254
					Std Dev:	0.488	0.488	0.332	0.332	0.184		0.001	0.334
					% rel SD	0.871	1.108	0.835	0.551	0.835		0.447	1.322

initial VS (kg)	0.1561	initial VS (%):	20.279
final VS (kg)	0.11668	final VS (%):	39.722
VS_f/VS_i	0.74746		

C-90

VOLATILE SOLIDS DATA

24% soil

Initial Conditions: **Total weight:** 790.132 grams VS = 156.1 g

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
24	95.1056	109.4065	103.531	100.3806	5.8752	41.083	58.917	37.394	62.606	20.774	0.6943	0.153	2.008604
24	98.0213	107.5073	103.825	101.7403	3.682	38.815	61.185	35.924	64.076	19.958		0.1526	2.238648
24	86.0061	105.7171	97.7986	93.4592	7.919	40.173	59.827	36.798	63.202	20.443		0.1529	2.081379
					Mean:	40.024	59.976	36.705	63.295	20.392		0.153	2.110
					Std Dev:	0.932	0.932	0.604	0.604	0.335		0.000	0.096
					% rel SD	2.328	1.554	1.645	0.954	1.645		0.098	4.551

initial VS (kg)	0.1561	initial VS (%):	19.756
final VS (kg)	0.15281	final VS (%):	36.705
VS_f/VS_i	0.9789		

VOLATILE SOLIDS DATA

26% soil

Initial Conditions: **Total weight:** 775.453 grams VS = 156.1 g

Final compost data:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
26	96.8029	107.3065	101.37	99.1224	5.937	56.523	43.477	49.207	50.793	27.337	0.72274	0.1546	0.9480
26	87.3173	100.3087	92.8861	90.1127	7.423	57.135	42.865	49.802	50.198	27.668		0.1543	1.1593
26	95.1946	106.0446	99.7975	*broke	6.247	57.577	42.423	-	**broke	-		-	-
26	95.106	106.0235	99.8458	97.5105	6.178	56.585	43.415	49.270	50.730	27.372		0.1546	0.9627
					Mean:	56.955	43.045	49.427	50.573	27.459		0.155	1.023
					Std Dev:	0.431	0.431	0.267	0.267	0.148		0.000	0.096
					% rel SD	0.756	1.001	0.540	0.528	0.540		0.097	9.414

initial VS (kg)	0.1561	initial VS (%):	20.130
final VS (kg)	0.1545	final VS (%):	49.427
VS_f/VS_i	0.98977		

26-C

VOLATILE SOLIDS DATA

28% soil

Initial Conditions: **Total weight:** 834.028 grams VS = 156.1 g

Final compost data:

Run 1:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
28	83.1248	95.4785	88.0564	85.6174	7.4221	60.080	39.920	49.456	50.544	27.476	0.78243	0.1545	1.0407
28	98.5764	105.4297	100.988	99.6342	4.441	64.805	35.195	56.144	43.856	31.191		0.1546	0.9566
28	62.1484	70.0213	64.9841	63.4267	5.037	63.982	36.018	54.921	45.079	30.512		0.1548	0.8465
28	76.1598	82.6027	78.4264	77.1523	4.176	64.820	35.180	56.212	43.788	31.229		0.1547	0.8792
					Mean:	63.422	36.578	54.183	45.817	30.102		0.155	0.931
					Std Dev:	1.959	1.959	2.777	2.777	1.543		0.000	0.075
					% rel SD	3.089	5.356	5.125	6.061	5.125		0.076	8.059

C-93

Run 2:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
28	85.1237	97.3489	89.4237	86.9995	7.9252	64.827	35.173	56.377	43.623	31.320	0.77612	0.1539	1.4087
28	80.7521	89.3662	83.3608	81.6576	6.005	69.716	30.284	65.289	34.711	36.272		0.1535	1.6936
28	93.4527	101.7548	95.9978	94.3531	5.757	69.344	30.656	64.622	35.378	35.901		0.1538	1.5026
28	76.8995	88.6313	80.6782	78.3491	7.953	67.791	32.209	61.638	38.362	34.243		0.1541	1.2927
					Mean:	67.919	32.081	61.981	38.019	34.434		0.154	1.474
					Std Dev:	1.926	1.926	3.516	3.516	1.953		0.000	0.147
					% rel SD	2.836	6.004	5.672	9.248	5.672		0.149	9.956

VOLATILE SOLIDS DATA

28% soil (continued)

** wb = wet basis
*db = dry basis

	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	% VS reduction
Results combined:	60.080	39.920	49.456	50.544	27.476	1.0407
	64.805	35.195	56.1443	43.8557	31.1913	0.9566
	63.982	36.018	54.9212	45.0788	30.5118	0.8465
	64.820	35.18	56.2119	43.7881	31.2289	0.8792
	64.827	35.173	56.377	43.623	31.320	1.4087
	69.716	30.284	65.2892	34.7108	36.2718	1.6936
	69.344	30.656	64.6222	35.3778	35.9012	1.5026
	67.791	32.209	61.638	38.362	34.243	1.2927
Mean:	65.671	34.329	58.082	41.918	32.268	1.2026
Std Dev:	2.9717	2.9717	5.0239	5.0239	2.7910	0.2958
% rel SD	4.53%	8.66%	8.65%	11.99%	8.65%	24.59%

initial VS (kg)	0.1561	initial VS (%):	18.716	
final VS (kg)	0.15465	final VS (%):	58.082	
VS_f/VS_i	0.99069			
initial VS (kg)	0.1561	initial VS (%):	as above	
final VS (kg)	0.1538	final VS (%):	as above	
VS_f/VS_i	0.98526			
average: initial VS (kg)	0.1561	initial VS (%):	18.716	
final VS (kg)	0.15422	final VS (%):	58.082	
VS_f/VS_i	0.98797			

VOLATILE SOLIDS DATA

30% soil

Initial Conditions: **Total weight:** 857.957 grams VS = 156.1 g

Final compost data:

Run 1:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
30	81.2145	92.3153	85.0421	82.6703	7.2732	65.520	34.480	61.966	38.034	34.425	0.72146	0.154	1.251
30	64.5984	77.3158	68.9157	66.2015	8.400	66.052	33.948	62.868	37.132	34.927		0.154	1.360
30	56.1564	61.4789	58.2287	57.0884	3.250	61.065	38.935	55.026	44.974	30.570		0.155	0.982
30	91.3218	99.1583	93.7485	92.0752	5.410	69.033	30.967	68.954	31.046	38.308		0.154	1.313
					Mean:	65.418	34.582	62.203	37.797	34.557		0.154	1.227
					Std Dev:	2.847	2.847	4.939	4.939	2.744		0.000	0.146
					% rel SD	4.353	8.233	7.940	13.068	7.940		0.148	11.920

Sb-3 C-95

Run 2:

Soil %	Empty wt	Wet wt	Dry wt	Ashed wt	Moisture wt	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	total wt (kg)	VS wt (kg)	% VS reduction
30	91.5468	98.7128	94.3874	93.0189	4.3254	60.360	39.640	48.176	51.824	26.765	0.79528	0.152	2.706
30	92.0315	103.4517	96.1851	94.0017	7.267	63.629	36.371	52.566	47.434	29.204		0.152	2.596
30	78.0827	84.5233	80.2764	79.0541	4.247	65.940	34.060	55.719	44.281	30.955		0.151	3.313
30	66.4859	77.948	70.1562	67.9724	7.792	67.979	32.021	59.499	40.501	33.055		0.152	2.934
					Mean:	64.477	35.523	53.990	46.010	29.995		0.152	2.887
					Std Dev:	2.831	2.831	4.158	4.158	2.310		0.000	0.274
					% rel SD	4.391	7.971	7.702	9.038	7.702		0.282	9.500

VOLATILE SOLIDS DATA

30% soil (continued)

** wb = wet basis
**db = dry basis

	% moisture **wb	% TS **wb	%VS *db	% FS *db	%OC *db	% VS reduction
Results combined:	65.520	34.480	61.966	38.034	34.425	1.251
	66.052	33.948	62.868	37.132	34.927	1.360
	61.065	38.935	55.026	44.974	30.570	0.982
	69.033	30.967	68.954	31.046	38.308	1.313
	60.360	39.640	48.176	51.824	26.765	2.706
	63.629	36.371	52.566	47.434	29.204	2.596
	65.940	34.060	55.719	44.281	30.955	3.313
	67.979	32.021	59.499	40.501	33.055	2.934
Mean:	64.947	35.053	58.097	41.903	32.276	2.0569
Std Dev:	2.8781	2.8781	6.1406	6.1406	3.4115	0.8590
% rel SD	4.43%	8.21%	10.57%	14.65%	10.57%	41.76%

initial VS (kg)	0.1561	initial VS (%):	18.194	
final VS (kg)	0.15419	final VS (%):	58.097	
VS_f/VS_i	0.98773			
initial VS (kg)	0.1561	initial VS (%):	as above	
final VS (kg)	0.15159	final VS (%):	as above	
VS_f/VS_i	0.97113			
average: initial VS (kg)	0.1561	initial VS (%):	18.194	
final VS (kg)	0.15289	final VS (%):	58.097	
VS_f/VS_i	0.97943			

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APPENDIX C-4
HEADSPACE OXYGEN AND METHANE GENERATION DATA

Soil Loading	Day	Gas Sampled	Pre-Aeration Cycle		During Aeration Cycle										
			30 min before cycle	1 min before cycle	Time in minutes (0 is start of aeration cycle)										
					0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
			Sample results as volumetric percent												
0	1	O_2	16	15	15	15	18	20	22	20	20	21	20	20	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	13	13	14	15	20	19	20	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	14	14	13	15	16	17	20	22	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	O_2	18	19	18	20	21	20	21	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	16	15	16	20	20	20	21	21	20	20	20	21	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	15	15	15	16	19	19	21	20	20	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
6	1	O_2	18	16	18	20	21	22	22	22	21	22	22	22	22
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	17	17	18	20	21	21	21	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	16	17	17	17	18	20	20	21	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
8	1	O_2	18	19	20	22	22	21	22	21	22	22	22	22	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	15	15	15	16	20	20	20	20	20	21	21	21	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	13	14	14	18	20	21	21	21	20	21	21	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1	O_2	18	17	18	21	20	21	20	20	20	20	20	21	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	14	14	14	18	20	20	20	20	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	12	13	14	15	17	19	21	21	21	21	20	20	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0

Soil Loading	Day	Gas Sampled	Pre-Aeration Cycle		During Aeration Cycle										
					Time in minutes (0 is start of aeration cycle)										
			30 min before cycle	1 min before cycle	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
			Sample results as volumetric percent												
12	1	O_2	17	17	18	20	20	20	20	20	21	21	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	16	15	16	19	21	21	21	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	12	11	10	16	20	19	20	20	20	21	20	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
14	1	O_2	18	16	16	20	20	20	20	20	20	21	20	20	19
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	15	15	17	17	18	18	20	20	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	12	10	10	10	12	12	17	17	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1	O_2	16	16	17	19	21	20	20	21	20	20	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	14	13	13	14	19	20	21	21	21	20	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	10	11	11	11	10	14	18	18	20	21	20	20	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
18	1	O_2	18	19	19	21	21	21	21	20	21	21	21	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	14	14	17	20	19	20	20	21	20	21	22	21	22
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	12	11	12	12	12	18	20	20	20	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1	O_2	17	16	17	20	21	20	21	20	20	20	19	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	13	12	13	16	17	20	20	20	21	21	21	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	O_2	10	10	10	10	11	15	16	15	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0

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Soil Loading	Day	Gas Sampled	Pre-Aeration Cycle		During Aeration Cycle										
					Time in minutes (0 is start of aeration cycle)										
			30 min before cycle	1 min before cycle	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
			Sample results as volumetric percent												
22	1	O_2	15	16	16	20	20	20	20	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	12	12	12	12	14	16	17	20	18	19	20	19	19
		CH_4	2	3	3	4	3	3	1	0	0	0	0	0	0
	10	O_2	9	9	9	10	9	10	11	12	10	10	18	20	20
		CH_4	4	3	4	4	3	3	2	0	0	0	0	0	0
24	1	O_2	16	16	16	20	20	21	21	21	20	20	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	10	9	8	9	10	10	11	18	20	19	20	20	20
		CH_4	3	3	3	3	2	3	2	1	0	0	0	0	0
	10	O_2	6	7	8	7	7	8	8	10	18	19	20	20	20
		CH_4	4	3	4	3	3	4	4	2	0	0	0	0	0
26	1	O_2	17	18	18	18	20	21	20	20	19	20	22	21	22
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	10	10	10	9	10	10	15	20	20	21	20	21	21
		CH_4	4	4	4	4	4	3	2	0	0	0	0	0	0
	10	O_2	8	6	7	6	9	8	10	13	19	20	20	21	21
		CH_4	4	4	4	4	4	3	3	1	1	0	0	0	0
28a	1	O_2	18	18	18	20	21	21	21	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	12	13	12	11	12	12	12	17	20	21	21	21	21
		CH_4	8	10	10	9	9	9	9	5	0	0	0	0	0
	10	O_2	2	1	2	1	2	3	1	2	2	2	3	3	5
		CH_4	15	16	15	14	15	13	15	15	15	16	15	16	16
28b	1	O_2	15	16	19	20	21	20	20	20	21	20	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	10	10	9	10	10	10	11	10	11	16	19	20	21
		CH_4	6	10	8	9	9	10	9	8	8	6	2	0	0
	10	O_2	0	1	1	1	1	1	1	1	0	1	0	3	2
		CH_4	13	13	13	14	13	14	12	12	13	14	14	14	14

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Soil Loading	Day	Gas Sampled	Pre-Aeration Cycle		During Aeration Cycle										
					Time in minutes (0 is start of aeration cycle)										
			30 min before cycle	1 min before cycle	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
			Sample results as volumetric percent												
30a	1	O_2	16	16	15	18	21	20	21	20	20	20	20	20	20
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	8	7	7	7	7	7	7	8	8	9	13	13	12
		CH_4	10	12	10	10	10	10	10	11	10	10	10	6	6
	10	O_2	0	0	0	0	0	0	0	0	0	0	0	0	4
		CH_4	16	15	16	16	16	16	16	16	16	16	16	16	15
30b	1	O_2	18	19	18	19	21	21	21	21	21	21	21	21	21
		CH_4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	O_2	6	7	6	6	7	6	7	7	7	6	6	7	8
		CH_4	9	9	10	9	8	9	9	10	9	9	9	8	7
	10	O_2	0	0	1	1	1	0	0	1	1	2	1	3	2
		CH_4	15	18	17	18	16	18	17	17	17	16	17	17	18

APPENDIX C-5
TPH DATA - WOODCHIPS AND BIOSOLIDS DATA

Woodchips

Run:	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	Total
Fox Lake, undried	38.46	12.67	30.79	157.09	947.43	1100	279.5	336.29	148.71	8537.34	11588.28
Fox Lake, dried	0	0	0	22.6	366.96	322.87	161.35	193.9	133.54	1581.79	2783.01
Pine Falls undried	632.3	115.99	143.01	559.13	404.14	850.54	721.8	292.58	0	10647.12	14366.61
Pine Falls dried	99.07	25.13	199.64	53.95	320.23	189.01	363.43	459.86	0	4641.17	6351.49

My woodchips

undried	239.13	169	98.01	321.55	1011.35	645.31	550.12	150.88	150.48	9908.75	13244.58
	254.87	158.74	87.46	355.32	1102.84	620.58	587.24	142.87	156.49	10103.59	13570
	261.8	175.84	94.22	289.11	980.56	630.42	569.99	145.33	148.23	9968.16	13263.66
mean:	251.9333	167.86	93.23	321.9933	1031.583	632.1033	569.1167	146.36	151.7333	9993.5	13359.41
St.Dev.	9.485084	7.027432	4.363538	27.03194	51.93034	10.1659	15.16675	3.350194	3.486644	81.53626	149.1109
% R.S.D.	3.764918	4.186484	4.680402	8.395185	5.034042	1.608266	2.664964	2.289009	2.297876	0.815893	1.116148
dried	15.77	2.89	0	61.11	380.32	220.44	115.17	12.1	45.31	2330.12	3183.23
	20.23	3.22	0	63.45	375.55	217.86	121.63	15.84	50.22	2298.41	3166.41
	18.55	3.11	0	61.81	368.79	215.45	122.44	14.2	51.73	2301.98	3158.06
mean:	18.18333	3.073333	0	62.12333	374.8867	217.9167	119.7467	14.04667	49.08667	2310.17	3169.233
St.Dev.	1.839154	0.137194	0	0.980657	4.730415	2.037553	3.253043	1.530693	2.740734	14.18187	10.46775
% R.S.D.	10.11451	4.464016	0	1.578565	1.261825	0.935015	2.716604	10.8972	5.583459	0.613889	0.330293

APPENDIX C-6
^{14}C GENERATION DATA

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

0% soil

Time	(reading - background)		% of original
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	na
2	0	0	na
3	0	0	na
4	0	0	na
5	0	0	na
8	0	0	na
9	0	0	na
10	0	0	na
11	0	0	na
14	0	0	na
	Total:	0	na

4% soil

Time	(reading - background)		% of original
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0.133	5.99E-08	2.85E-05
9	0	0	0
14	1.607	7.24E-07	0.000344
	Total:	7.84E-07	0.000372

6% soil

Time	(reading - background)		% of original
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0.046	2.07E-08	6.38E-06
5	0	0	0
9	1.333	6E-07	0.000185
14	0.03	1.35E-08	4.16E-06
	Total:	6.35E-07	0.000196

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

8% soil

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
8	6.067	2.733E-06	0.000619
9	2.900	1.306E-06	0.000296
10	0	0	0
11	0	0	0
14	6.333	2.853E-06	0.000646
	Total:	6.892E-06	0.001562

10% soil

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	1.633	7.356E-07	0.000131
3	0.067	3.018E-08	5.36E-06
4	0	0	0
5	0.3	1.351E-07	2.4E-05
6	1.033	4.653E-07	8.27E-05
9	0	0	0
10	0	0	0
12	0.333	1.5E-07	2.66E-05
14	0	0	0
	Total:	1.516E-06	0.000269

12% soil

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	0.782	3.523E-07	5.09E-05
14	0.133	5.991E-08	8.65E-06
	Total:	4.122E-07	5.95E-05

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

14% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	0	0	0
3	0	0	0
4	0.3	1.35E-07	1.63E-05
5	0	0	0
6	0	0	0
9	0	0	0
10	0.467	2.1E-07	2.54E-05
12	0	0	0
14	0	0	0
	Total:	3.45E-07	4.18E-05

16% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	0	0	0
3	0	0	0
4	3.333	1.5E-06	0.000155
5	0	0	0
6	0	0	0
9	0	0	0
10	0	0	0
12	0	0	0
14	0	0	0
	Total:	1.5E-06	0.000155

18% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	0	0	0
14	2.149	9.68E-07	8.7E-05
	Total:	9.68E-07	8.7E-05

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

20% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	5.933	2.67E-06	0.000211
3	9	4.05E-06	0.00032
4	0.567	2.55E-07	2.01E-05
5	2.7	1.22E-06	9.59E-05
6	2.467	1.11E-06	8.76E-05
7	0.467	2.1E-07	1.66E-05
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
	Total:	9.52E-06	0.000751

22% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0.133	5.99E-08	4.19E-06
5	0	0	0
9	0	0	0
14	0	0	0
	Total:	5.99E-08	4.19E-06

24% soil

Time	(reading - backgrou	% of original	
	^{14}C	^{14}C	^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	0.144	6.49E-08	4.05E-06
14	0.299	1.35E-07	8.4E-06
	Total:	2E-07	1.25E-05

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

26% soil

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	3.124	1.407E-06	7.89E-05
14	4.152	1.87E-06	0.000105
	Total:	3.277E-06	0.000184

28% soil run 1

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	0.845	3.806E-07	1.93E-05
3	1.266	5.703E-07	2.89E-05
4	0	0	0
5	3.447	1.553E-06	7.87E-05
6	0	0	0
7	0	0	0
	Total:	2.504E-06	0.000127

28% soil run 2

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	0	0	0
14	0.183	8.243E-08	4.18E-06
	Total:	8.243E-08	4.18E-06

^{14}C generation data

Notes: 1. if reading - background was <0, 0 was used.
i/g diesel 2. Initial conc of 1-^{14}c-octadecane was 2.536 uCi/g diesel

30% soil run 1

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0.233	1.05E-07	4.83E-06
	Total:	1.05E-07	4.83E-06

30% soil run 2

Time	(reading - background) ^{14}C	^{14}C	% of original ^{14}C
(days)	(DPM)	(µCi)	(%)
1	0	0	0
5	0	0	0
9	0	0	0
14	0	0	0
	Total:	0	0

APPENDIX D
NaOH TRAPS AND DIESEL QUANTITY CALCULATIONS

CO2 generation calculations *note: 0.6 kg of organic amendment mix= 1 reactor

-assumptions: 60% [redacted] VS from biosolids are biodegradable
5% [redacted] of VS from woodchips are biodegradable
[redacted]odegradation of 75-80% of biodegradable VS will occur over 14 day run

-in one reactor, 0.6 kg organic amendments

gives:	0.301 kg wet biosolids	which is:	0.094634 kg dry biosolids (0.2064 kg water)
	0.299 kg wet woodchips		0.175453 kg dry woodchips (0.1234 kg water)
per 0.6 kg of organic amendment mixture		per 0.6 kg of organic amendment mixture	

total dry wt = 270.1 g.

Volatile Solids:

woodchips: 68.2% dry basis
or 0.119659 kg woodchips VS per 0.6 kg organic amendment mix
which is 0.005983 kg biodeg woodchips VS per 0.6 kg organic amendment mixture
biosolids: 38.63% dry basis
or 0.036557 kg biosolids VS per 0.6 kg organic amendment mix
which is 0.018279 kg biodeg biosolids VS per 0.6 kg organic amendment mixture

for a total of: 0.024262 kg biodeg VS per 0.6 kg organic amendment mixture

total VS = 156.1 g

biodegradable material

assuming 80% of the biodegradable VS is converted during the composting run, that means:
0.019409 kg biodeg VS are degraded per 0.6 kg organic amendment mixture

Carbon:

woodchips: 37.88 % OC dry basis
or 0.066462 kg woodchip OC per 0.6 kg organic amendment mixture
biosolids: 21.46% OC dry basis
or 0.020309 kg biosolid OC per 0.6 kg organic amendment mixture
for a total of: 0.08677 kg OC per 0.6 kg organic amendment mixture

or: 7.224831 moles of C per 0.6 kg organic amendment mixture

carbon

Nitrogen:

woodchips: 0.41% wet basis
or 0.001226 kg woodchip nitrogen per 0.6 kg organic amendment mixture
biosolids: 3.11% wet basis
or 0.093611 kg biosolid nitrogen per 0.6 kg organic amendment mixture
for a total of: 0.094837 kg nitrogen per 0.6 kg organic amendment mixture
or: 6.774064 moles of N per 0.6 kg organic amendment mixture

nitrogen

Total Parameters:

weight in reactors:	0.6	kg of organic amendment mixture
minus carbon	-0.08677	
minus nitrogen	-0.09484	
minus water	-0.3298	this is: 18.30 moles of O and 36.60 moles of H
	0.088593	

which is??? →

Using the equation from Tchobanoglous et al (1993)
$C_aH_bO_cN_d + ((4a+b-2c-3d)/4)O_2$ gives $aCO_2 + ((b-3d)/2)H_2O + dNH_3$

from calculations above:
a=7.22
b=36.6
c=18.3
d=6.77

which means that: 2.142 moles of O2 will be needed to convert 1 mole of organic amendment mixture
or: 68.54 g of O2 will be needed per 511.26 g of organic amendment mixture
or: 0.0804 kg of O2 per 0.6 kg of organic amendment

Safety factor (after Larsen 1998): Oxygen required: 0.1608 kg

O-2

in a 0.6 kg reactor only 0.0243 kg are biodegradable; (0.0194) kg are degraded (80% of 0.0243 kg)

so

$$\frac{7.22 \text{ mole } CO_2}{\text{mole org amend.}} = \frac{7.22(44.01 \text{ g/mol})}{511.26 \text{ g org amendment}}$$

$$= \frac{0.622 \text{ g } CO_2}{\text{g org amendment}}$$

in 1 reactor, 0.0194 kg degradable

which is $\frac{0.622 \text{ g } CO_2}{\text{g org am.}} * 0.0194 \text{ kg org amend. degradable}$

$= 0.0012 \text{ kg } CO_2$ produced per reactor

assume: CO_2 distribution curve 

day 0-1: 25% CO_2
1-2: 30% CO_2
2-3: 20% CO_2
3-4: 15% CO_2
4-5: 10% CO_2
5-6: 5% CO_2

14 ↓: 5% CO_2

* conservative estimate! adds to 145%.

need to trap max of 30% of CO_2 in 1 day

30% of 0.0121 kg = 3.63 g CO_2 in 1 day

= 0.0825 moles CO_2 in 1 day

0.830-0.876 range

normal sp g d #2 → 0.855-0.87 normal

take 0.830 (conservative)

2.22×10^6 dpm = 1 µCi

I have 100 µCi

I want $\frac{8\,\mu Ci}{g\ diesel}$

$$100\,\mu Ci * \frac{g\ diesel}{8\,\mu Ci} * \frac{mL}{0.830\,g} = 15.06\ mL$$

---

min diesel

1) $0.0834\,g * \frac{1mL}{0.830\,g} = 0.1\ mL$

$$0.1mL * \frac{8\,uCi}{g\ diesel} * \frac{0.83\,g}{mL} = 0.664\,\mu Ci = 1,474,000$$

2) ~~$\frac{g\ diesel}{0.830}$~~

ASSUMING SP GV IS OK:

min ^{14}C → 0.664 µCi → 1,474,000 dpm per mL | 0.1 mL

	in 20 mL	
day min → 2 → 30% → 442,200 dpm	2211 dpm	221.1 dpm
day max → 9 → 5% → 73,700 dpm	3685 dpm	36.85 dpm

max: 6.856 µCi (30% soil) = 1.52×10^7 dpm

		5 mL in 200 mL	0.1 mL
day max:	30% = 4,566,000 dpm	22830 dpm	2283 dpm
min:	5% = 761,000 dpm	3805 dpm	380.5 dpm