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#### EXPERIMENTAL OBSERVATIONS OF COMPOSTING DAIRY MANURE SOLIDS

By

Stephen Earl Ferns

#### A THESIS

# Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

# MASTER OF SCIENCE

# in

# Agricultural Engineering

Department of Agricultural Engineering

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#### ABSTRACT

#### EXPERIMENTAL OBSERVATIONS OF COMPOSTING DAIRY MANURE SOLIDS

By

Stephen Earl Ferns

Dairy manure solids (DMS) were composted in a batch windrow process of 3 weeks duration with weekly turnings. Diffusion or natural convection provided heat and mass transfer. Temperature, gas concentration (O2 & CO2), ambient conditions, insitu physical properties and pile size were monitored. A temperature and gas probe and a rotary corer developed show promise for future insitu sampling in composting systems of this type. Sensitivity analyses were performed on the experimental methods and suggestions for improvements were made.

Results show that the assumption of spatially constant physical and thermal properties used in a previous model of distributed heat and mass transfer in compost windrows is not justified in all cases. Significant changes in physical properties over time were not observed.

DMS compost behaved similarly to other compost substrates. However, DMS composted at higher moisture contents and lower maximum temperatures were observed than with other compost substrates. Distinct color zones that correlated with time-temperature patterns were observed in the windrow cross-sections. Analysis of time-temperature patterns indicated areas where either significant thermal death or regrowth of mastitis-causing coliform organisms could occur. Several methods were discussed for managing the DMS composting process in order to produce acceptable dairy bedding material.

Major Professor

Major Professor

Department Chairman

To my wife Lori.

ł.

#### ACKNOWLEDGMENTS

Many individuals have contributed to the success of my MS studies and research at MSU. My Co-Major Professors, Dr. John Gerrish and Dr. Ted Loudon provided direction, assistance and support. Dr. Gerrish was an inspiration in his ability to creatively solve research problems. Dr. Loudon provided pactical research advice and was generous in his sharing of knowledge on soil and water engineering. Dr. Fred Bakker-Arkema served on my committee and provided insight into heat and mass transfer processes and vigorously tried to move me along in my program. Dr. Larry Segerlind graciously discussed applying Finite Element modeling to DMS composting and served on my committee. One of my biggest disappointments was not being able to actually use this in the thesis.

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#### CHAPTER 1

#### INTRODUCTION

In the last decade the use of separated dairy manure solids as a bedding material for dairy cattle has received increasing attention and use. Depending on herd size and the availability and cost of other bedding materials, the separated dairy manure solids can provide an economic alternative (Keys et al., 1977; Allen et al., 1979). The direct economic benefits in dairies using liquid flush manure handling systems can be augmented by savings from decreased labor in the manure flushing system, the construction of smaller waste storage lagoons and less frequent removal of manure solids (Hermanson, 1985; Lindemann, 1985). Some studies have shown that cows prefer separated manure solids to other types of bedding (Keys et al, 1977).

#### <u>1.1:</u> <u>Criteria for Use of Dairy Manure Solids as a Bedding</u> <u>Material</u>

In order to be a satisfactory bedding material, the dairy manure solids must meet several criteria. Moisture content affects general cow cleanliness and the ease of handling the bedding material. More importantly, high levels of certain micro-organisms in bedding material have been associated with mastitis in dairy cows (Bramely and

Neave, 1975).

#### 1.2: Effects of Mastitis on the Dairy Industry

#### 1.2.1: Physical Effects

Mastitis is an infection of the mammary gland. In dairy cows it is characterized by swelling, heat, redness, pain and disturbed function. Clinical signs of the disease are a result of the cow's defense mechanism attempting to destroy invading micro-organisms, return milk production to normal and repair the damaged gland (Jarrett, 1981). Mastitis can begin with injury to the teat or the entry of pathogenic bacteria into the teat (Bramley, 1974; Carroll, 1977). The entry of pathogenic bacteria can be affected by the milking routine, disease prevention procedures, faulty milking machines and the sanitary quality of the cow's environment, ie. the bedding and water supply.

The severity of mastitis attacks can range from chronic, low-level infections which affect the quality and quantity of the milk produced, to peracute in which all signs of inflammation are present, together with fever, depression, shivering, loss of appetite and rapid weight loss (Jain, 1979). Peracute mastitis can lead to the cows' death within hours; cows that survive may not recover their milk production and must be culled.

Mastitis severity is related to the type of bacteria and the resistance of the host (Jarrett, 1981). The pathogenicity of coliform organism serotypes, for instance, varies widely (Carroll et al., 1973). Dairy cows are

particularly susceptible to coliform mastitis just prior to parturition and in the early stages of lactation (Bramely, 1974; Eberhart & Buckelew, 1972).

#### 1.2.2: Economic Effects

Economic losses from bovine mastitis can be serious. Estimates of the United States' annual losses due to mastitis during 1976 were \$1,294 million (Blosser, 1979). Reduced production and discarded milk accounted for \$897 (69.3 %) and \$142 (11.0 %) million, respectively. Increased replacement costs due to death and early culling caused a \$103 (8.0 %) million estimated loss.

#### 1.3: Micro-organisms Associated with Mastitis

#### 1.3.1: General Organisms

A wide variety of micro-organisms has been associated with mastitis. Streptococcal and staphylococcal organisms account for many cases of chronic, low level mastitis that reduce the quantity and quality of milk production (Nat. Masitis Coun., 1978). Coliform organisms have been implicated in outbreaks of peracute mastitis and the subsequent death of cows (Nat. Mastitis Coun., 1978). Bovine mastitis produced by Cornebacteria (Packer, 1977a), Psuedomonas aeruginosa (Packer, 1977b), mycoplasma (Jasper, 1977) and yeast-like fungi (Farnsworth, 1977) have also been reported.

#### 1.3.2: Coliform Organisms

Mastitis caused by coliform organisms is of particular concern when dairy manure solids are used as bedding.

"Coliform" loosely refers to lactose-fermenting organisms of the family Enterobactericeae, including the genera Escherichia, Klebsiella, and Enterobacter (Eberhart, 1977). Coliform organisms are prevalant in the dairy environment (Brander, 1973). Levels of coliform organisms greater than 1x10<sup>6</sup> have been associated with outbreaks of mastitis (Bramely, 1974; Bramely and Neave, 1975). This level of coliform organisms occurs in many types of fresh and used bedding in dairy environments (Bramely and Neave, 1975; Neave and Oliver, 1962; Jasper et al., 1975, Carrol and Jasper, 1979; Bishop et al., 1980; Rendos et al., 1975). High-producing cows tend to spend longer times in contact with bedding materials than low producers (Francis, 1981); this leads to high temperatures and increased coliform growth in bedding used by high producers (Francis, 1981).

The existance of high coliform organism levels does not not necessarily lead to coliform mastitis, however. Coliform mastitis is considered a disease of glands not affected by other pathogens (Jain, 1979). Colonies of Staphylococcus aureus and Streptococcus agalactia adhere much more easily to the teat than do coliform organisms (Frost, 1977). In the absence of specific therapy, colonies of S. aureus and S. agalactia grow into the cow's teats and produce low levels of chronic mastitis (Jain, 1979). Coliform infections are difficult to superimpose upon other infections. 500,000 leukocytes/ml of foremilk from any irritant, will usually prevent the establishment of

experimental innoculums of coliforms (Schalm et al., 1971).

Significant progress has been made in the development of programs to reduce Streptococcus agalactiae and Staphylococcus aureus (Carroll, 1977). These programs for teat dipping and therapy of non-lactating cows are not effective against coliform organisms, however (Carroll, 1977; Eberhart, 1977). The removal of the staphylococcal and streptococcal infections opens the way for infection by coliform organisms.

# 1.4: Treatment of Dairy Manure Solids for Bedding 1.4.1: General Treatment Methods

One means of reducing the incidence of coliform mastitis is to treat the bedding material so that it will not support high levels of the organisms. Early work with paraformaldehyde indicated that its application would initially reduce levels of coliform organisms (Bramely and Neave, 1975). Recovery of coliform numbers was swift, however, and the economics of frequent chemical applications was judged to be prohibitive (Bramely and Neave, 1975). The use of lime additions to raise pH levels has been used with some success (Smith, 1985).

#### 1.4.2: Treatment by Composting

The application of composting to reduce coliform numbers and produce a relatively inert bedding material from separated dairy manure solids has also been attempted (Carroll and Jasper, 1979; Bishop et al., 1980; Allen et al., 1980). Composting has been shown to reduce the numbers

of mastitis-causing pathogens below the critical level of  $1 \times 10^{6}$  (Carroll and Jasper, 1978; Bishop et al., 1980; Allen et al., 1980). While regrowth of mastitis causing organsism has been noticed in compost used as bedding (Bishop et al., 1981), similar levels of regrowth have also been shown in other bedding materials (Rendos et al., 1975). Furthermore, the compost used in these experiments was not subjected to an intensely managed compost process such as a force aeration system.

Coliform control in composting dairy manure solids can be achieved in two manners. Temperatures inside compost piles of refuse and sewage sludge reach 80°C (Wiley, 1957; Shultze, 1962; Willson et al., 1980). Dairy manure solid compost temperatures up to 55°C have been reported (Allen et al., 1980). Bramely and Neave (1975) found that maintaining a temperature of 50°C in sawdust bedding samples killed the organisms, while 30 and 40°C temperatures led to increased numbers. Secondly, if the pile is correctly managed, the substrate should be reduced, thus inhibiting regrowth.

#### 1.5: The Composting Process

#### 1.5.1: Definition

Composting is a microbial self-heating process in which heat given off during aerobic respiration, in conjunction with reduced local oxygen concentration, depleted substrate, or extreme moisture level, tends to limit microbial growth (Finstein et al., 1980). Heat transfer and mass transfer of

oxygen, water and carbon dioxide is governed by diffusion, natural convection, forced convection or by a combination of processes.

#### 1.5.2: Parameters Affecting Composting

Research on composting has focused on empirical descriptions of the overall composting process and the impact of selected parameters on the desired objectives (Snell, 1957; Schulze, 1962; Jeris and Regan, 1973a,b,c). Temperature, oxygen level, moisture content, free air space and substrate properties, such as the amount of volatile solids present and the carbon/nitrogen ratio, have been found to be important parameters.

#### 1.5.3: Spatial Variability

The distribution of temperature and oxygen in a compost pile has been found to be non-uniform (Lambert, 1941). Furthermore, Carrol and Jasper (1978) have observed that the distribution of mastitis-causing organisms within a composting pile varies with time and temperature.

#### <u>1.5.4:</u> <u>Need for Distributed Heat and Mass Transfer</u> <u>Composting Model</u>

Because of the spatial variability and the difficulty in obtaining time-temperature relationships, it is difficult to predict the overall level of mastitis-causing organisms in a compost pile based on grab samples. This is particularly true when different parts of a compost pile are mixed together and used as bedding material. For example, if 90 % of the compost has coliform levels of 1x10<sup>3</sup> per gram of bedding, and only 10 % has levels of 1x10<sup>7</sup>, the

thoroughly mixed pile will still have dangerous levels of  $1 \times 10^6$  per gram of bedding. Extensive experimentation is necessary to determine the correct pile size and shape to achieve uniform reductions in mastitis-causing organisms. A model that predicts spatial and temporal changes in temperature would show where in the pile treated bedding material could be obtained.

1.5.5: Modeling Composting Heat and Mass Transfer Processes

Little work has been done to model composting. Comprehensive simulations of continuous-feed completelymixed and batch models of the composting process have been developed by Haug (1980). Finger (1975) developed a distributed heat-and mass-transfer model for windrow composting that is based on constant property thermal heat conduction and the diffusion of oxygen into the compost pile.

Modeling spatially-distributed heat-and-masstransfer processes in a compost pile can be improved. Haug's models, while sound in theory, are not distributed models. Finger's model, while a distributed model, has four potentially serious shortcomings: (1) it does not take into account the reduced respiration that occurs at high temperatures; (2) it ignores the role that water could play in the heat-and-mass-transfer process, (3) it is based on constant physical and thermal properties, and, (4) it can be applied only to rectangular geometries.

#### 1.5.6: Recent Advances in Composting

**Recent research** has indicated the nature of the shortcomings of Finger's model. McKinley and Vestal (1984) found that the maximal respiration for sewage sludge composting occurs in the range of 25°C to 45°C. Other studies (Finstein et al., 1980) have noted that the temperature optimum for composting is in the range of 50°C to 55°C. Moisture content has been found to affect the thermal and physical properties of compost. Bonhoff, et al. (1984) found that for separated dairy manure, the specific heat, thermal conductivity, thermal diffusivity, and free air space are functions of the percent moisture content. The thermal diffusivity is also a function of temperature and bulk density. Mears et al. (1975) found that the specific heat and thermal conductivity of swine manure compost is a function of moisture content. Oxygen diffusion rates in ground garbage compost material are linearly related to the free inter-connected air space and inversely affected by increases in moisture content (Shell, 1955). Water can play a large role in heat and mass transfer within a compost pile. Finstein et al. (1983) estimated that when vaporization is used as a strategy in forced aeration systems for temperature control, almost 88 % of the heat removal is through vaporization, while only 10 % is through dry air convection and 2 % by conduction. Bulk density increases and pile volume decreases with time in long-term undisturbed swine manure compost windrows (Mears et al.,

1975).

Reliance on experience with other types of composting may not lead to an accurate understanding of the problems related to dairy manure solids composting, however. Creation of adequate free air space (air filled porosity) is an important concern with sewage sludge composting because of its small particle size (Haug, 1980). Mote and Griffis (1980) found that moisture management is of crucial importance with composting cotton gin trash. Composts made from different carbon sources exhibited very different temperature profiles when carbon/nitrogen ratio and bulk density were held constant (Mote and Griffis, 1980). Since the few studies of composting dairy manure solids (Carrol and Jasper, 1978; Bishop, et al., 1980; Allen et al., 1980) do not focus on the actual composting process, it would be desirable to observe the composting of this substrate as part of an overall modeling effort.
### CHAPTER 2

# OBJECTIVES

The objectives of this research are (1) to conduct experimental studies of a partially enclosed windrow dairy manure solids (DMS) composting systems aimed at assessing the importance of variables affecting composting heat and mass transfer; (2) to assess the accuracy of the data collection effort; and (3) to make suggestions for future modeling of heat and mass transfer in DMS composting.

#### CHAPTER 3

#### LITERATURE REVIEW

#### 3.1: Description of Composting

Composting is a member of a class of processes that exhibit self-heating behavior (Cooney and Emerson, 1964). There is general agreement about the sequence of events leading to self-heating and, potentially, the spontaneous combustion of materials.

... If the material is reasonably fresh, the initial warming may be ascribed in part to the enzymatic activities of the still living plant material itself. However, it is generally conceded that the major buildup of heat results from the metabolism of the mixed saprophytic microbial flora that promptly develops. The temperature rises quickly,...often in a matter of hours if the decomposing material is finely divided and rich in readily available nutrient (such as fresh grass, chopped guayule, or manure), and soon passes the optimum for mesophilic forms. Here the thermophiles become of critical importance; they multiply rapidly and raise the temperature to the peak that can be reached by microbial activity--about 70°C or slightly higher. Subsequent heating results then from the autocatalytic chemical processes which can begin to operate at this temperature. The processes cause further heating, marked chemical changes in the heating mass, and ultimate ignition if the necessary conditions are maintained (Cooney and Emerson, 1964).

Composting differs from this general course of events in two manners. Since most composting processes involve dead or waste materials, the inital temperature rise is primarily caused by mesophilic saprophytic microorgansims

instead of the respiration of live plant cells. Secondly, temperatures do not generally reach the autocatalytic stage. Instead, temperatures are maintained at levels close to the maximum temperature for thermophilic growth until either the microbial population is so debilitated that it cannot support the high temperatures (Finstein, 1980), moisture content is reduced to inhibitory levels, or the substrate is exhausted (Finstein and Morris, 1975). At this point the temperatures begin to fall.

## 3.2: Analogous Systems

Insight into the underlying principles of dairy manure solid composting can be gained from a number of sources. Work in the late 19th and early 20th century led to a basic understanding of the self-heating and spontaneous combustion of a variety of agricultural products (Cohn, 1889; Miehe, 1905, 1930, Waksman et al.,1939). Some of the products investigated include hay, manure, barley, cornmeal, cracked corn, oats, cotton, hemp and hops (Cooney and Emerson, 1964). Self-heating caused large losses from fires and overheating and was estimated to be over \$20 million per year in the 1920's (Browne, 1929). Losses due to overheating and spontaneous combustion have also been noted in the peat (Finnish Peatland Society, 1982) and forest products (Hajny, 1966) industries.

On the positive side, microbial thermogenesis has been used to process a number of important products including cacao (Chatt, 1953), tobacco (Garner, 1946), horticultural

container media (Hoitink and Poole, 1980) and composts for mushroom production (Haiser and Sinden, 1953)

The application of composting to waste processing and treatment has also been extensively studied. Substrates examined include municipal wastes (Jeris and Reagan, 1973), leaves (Strom et. al., 1980), sewage sludge (Haug, 1979), septage (Lombardo, 1977), fruit and vegetable cannery wastes (Rose et al., 1965), cotton gin trash (Griffis and Mote, 1978), grain dust (Chang et al., 1980), and horse (Pizer, 1950) swine (Martin et al., 1974), poultry litter (Bell and Pos, 1971), and dairy manure (Hummel and Willson, 1975).

3.3: Microbiology

## 3.3.1: General

The growth of a micro-organism in a favorable environment procedes as shown in Figure 3.1. There is an initial period of adjustment to the environment, called the lag phase. Growth begins and accelerates into a period of rapid and constant exponential growth, called the



Figure 3.1: Hypothetical bacterial growth curve (From Olson and Nottingham, 1980)

exponential or logarithmic growth phase. This growth is eventually slowed and then stops due to the accumulation of toxic materials or depletion of nutrients. At this point, the stationary phase, cell division and death are in approximate balance. The final phase occurs when cell death becomes greater than new cell production (Olson and Nottingham, 1980).

The temperature ranges for growth can be used to distinguish between three major groups of micro-organisms. These groups are shown in the Table 3.1. Within each group there are organisms that can survive into the temperature ranges of the adjacent groups (Olson and Nottingham, 1980).

Table 3.1: Growth temperatures for micro-organisms.

Group	Minimum	Temperature (°C) Optimum	Maximum
Psycrophiles	-5 to +5	12 to 15	15 to 20
Mesophiles	5 to 15	30 to 45	35 to 47
Thermophiles	40 to 45	55 to 75	60 to 90

# 3.3.2: Types of Micro-organisms

A wide variety of micro-organisms have been identified in composts. Bacteria (including actinomycetes) and fungi are the predominant organisms found.

# 3.3.2.1: Bacteria and Actinomycetes

Bacteria have a number of morphological forms and are typically unicellular, but multicellular associations are

common. These associations can be true multicellular states or accumulations due to cell division. Actinomycetes have an elaborate multicellular structure that arise from a single reproductive cell. Extensive chains and branches develop into mycelia which structurally resemble molds. Actinomycete filaments are one tenth to one fourth the diameter of fungi; actinomycetes have a procaryotic structure compared with eucaryotic fungi, as well as biochemical and sexual differences (Haug, 1980).

The most common mode of bacterial reproduction is by binary fission, although sexual reproduction or budding can also occur in some cases. When unfavorable environmental conditions are encountered, some bacteria are capable of forming dormant cells which are more resistant to harsh environmental conditions. These forms include endospores, cysts, and exospores. Endospores are the most stable of the three forms (Haug, 1980).

### 3.3.2.2: Fungi

Fungi are eucaryotic and heterotrophic spore-bearing organisms that lack chlorophyll (Atlas and Bartha, 1981). Slime molds and true fungi make up the two broad divisions of fungi. The true fungi can be further divided into molds and yeasts. Both aerobic and anaerobic metabolism is observed among yeasts, while molds are aerobic (Haug, 1980). Fungi can tolerate low moisture conditions, have a larger optimum pH range and often have a lower nitrogen requirement than bacteria (Haug, 1980). Bacteria and fungi rely on similar organic substrates in composting systems and they are often in direct competition.

## 3.3.3: Compost Microbial Ecology

### 3.3.3.1: General

Environmental conditions determine which organisms can be present on a sustained basis in a given ecosystem. From an ecological standpoint the interaction between a biological system and the abiotic environment is best described by Oden's Combined Law, which states

... the presence and success of an organism or a group of organisms depends upon a complex set of conditions. Any condition which approaches or exceeds the limits of tolerance is said to be a limiting condition or a limiting factor (Atlas and Bartha, 1981).

Atlas and Bartha (1981) discuss the wide variety of environmental factors that can affect micro-organism growth: nutrients, temperature, water activity, pH, redox potential, pressure, and inhibitors. Tolerance ranges for any one parameter are interactive with other parameters. Nutrients or inhibitors must not only be present in the microorganism's environment, but they must also be in a form that is available to the micro-organism. The microhabitat of a micro-organism exerts the most direct effect on microbial growth and survival. The ability of micro-organisms to alter their environment can have a positive, negative or neutral effect on what microbial populations will be present.

#### 3.3.3.2: Temperature

The metabolic activity of an organism is affected by temperature. Higher, but non-lethal temperatures increase metabolism. The change in enzyme activity caused by a  $10^{\circ}$ C rise in temperature is called the  $Q_{10}$  value (Atlas and Bartha, 1981). Experimentally determined  $Q_{10}$  values for forced aeration garbage compost are shown in Table 3.2 (Moore, 1958; Wiley and Pierce, 1955).

Temperature levels affect the length of time for a new generation of micro-organisms to be produced, or the generation time. Figure 3.2 shows a curve for a typical mesophile (E. coli). Initially, as temperatures increase, growth also increases and generation times decrease. In the optimal growth range, generation times are short and fairly constant. Generation times go to infinity at a temperature only slightly greater than the optimal growth maximum (Olson and Nottingham, 1980).

Despite the general increases in biochemical activity with temperature, thermophiles have longer generation times than mesophiles and have lower cell yields in proportion to the amount of substrate utilized. This occurs because thermophillic organisms spend a great deal of time and energy repairing heat damage (Atlas and Bartha, 1981).

Micro-organisms make a number of adaptations to high temperature conditions (Atlas and Bartha, 1981). These adaptations include increases in the proportions of saturated lipids in membranes, synthesis of heat resistant

Temperature Range (?C)	Moore (1957)	Q <sub>10</sub> Wiley and Pierce (1955)
30 to 40	2.6	1.70
40 to 50	1.80	1.65
50 to 60	1.77	1.60

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Table 3.2:  $Q_{10}$  values for garbage composts.



Figure 3.2: Effect of temperature on the generation time of a typical mesophile (Escherichia coli) (Adapted from Olson and Nottingham, 1980) enzymes, and the inactivation of different enzyme systems at different temperatures. In addition, thermophilic organisms exhibit amino-acid and growth factor requirements at high temperatures that are not apparent at optimal temperatures. The maximum heat tolerence of vegetative thermophiles is correlated with the heat stability of their ribosomes.

When temperatures exceed the optimum for each organsim, injury or death can occur. Mild time/temperature exposures above the optimum temperature can cause stress which leads to injury. While an injured cell may remain viable, it may be unable to reproduce until the injury is healed (Olson and Nottingham, 1980; Busta, 1978).

The type of organism can affect survival rates. Spores of bacteria are resistant to high temperatures. Survival for minutes at 120°C or for hours at 100°C is not uncommon. Vegetative cells are killed after brief exposures to 70 to 80°C whether they are spore-formers or not (Olson and Nottingham, 1980).

A number of possible mechanisms have been proposed to explain the lethal influences of temperature on vegetative bacteria, including (1) coagulation of protein; (2) inactivation of enzymes; (3) disruption of cellular lipids; (4) damage to the genetic apparatus; (5) breakdown of RNA (Allwood and Russell, 1970).

Adams (1978) reviewed the heat injury of bacterial spores. Spore injury manifestation can fall into four major classes:

....(1) requirements by survivors for non-nutrient germination stimulants, (2) modified optimum temperatures for the enumeration of survivors, (3) increased sensitivity of survivors to inhibitors, and (4) altered nutritional requirements by survivors. Others, such as changes in the influence of pH, or Eh, and the choice of the recovery medium, have not been studied sufficiently to place them in specific classes (Adams, 1978).

Spores must germinate and complete outgrowth before vegetative cell growth can begin (Adams, 1978). During this period, the resistance of a spore to environmental stresses caused by heat, radiation, chemicals and extreme pH decreases. Spore germination is a multistage process that is mediated by a variety of agents (Adams, 1978). Injury that is expressed during outgrowth can involve a number of spore structures and metabolic activities.

Actinomycete temperature optima are not well defined (Finstein and Morris, 1975). Some researchers report temperature maxima in the range of 55°C, while others have found actinomycetes at temperatures up to 75°C.

Data on temperature ranges for thermophilic fungi have been presented (Cooney and Emerson, 1964). The minimum growth temperature is between 20 and 30°C; the maximum temperatures are 55 to 60°C. The relationship between temperature and growth of 6 fungi isolated from municipal waste compost was studied by Kane and Mullins (1973). Growth of fungal colony diameters was greatest in a range of 35 to 50°C. Between 55 and 60°C the growth dropped to zero. A study of the temperature and pH optima for 21 species of both thermophilic and thermotolerant fungi was conducted by Rosenburg (1975). His results agreed well with those of Kane and Mullins. No correlation was found between temperature optimum and pH optimum among members of the group tested.

An organism's resistance to these higher temperatures is expressed as the thermal death time. The thermal death time is the amount of time at a particular temperature that is required to kill a given number of organisms (Atlas and Bartha, 1981). By plotting the numbers of micro-organisms that survive a given temperature after a certain time on a semi-logaritmic plot, the decimal reduction value  $(D_r)$ , or time to give a ten-fold reduction, can be calculated (Atlas and Bartha, 1981). Some common decimal reduction times are given in Table 3.3.

The decimal reduction time for a given organism will change with temperature. By plotting the  $D_r$  values for each temperature on semilog paper, a straight line will generally be formed if death is first-order. The slope of this line, z, is the temperature interval required for a log reduction in the  $D_r$  value (Atlas and Bartha, 1981). Values of z for selected microorganisms are given in Table 3.4. Values of z are not constant over the entire temperature range because the value becomes infinite at some point (Hansen and Riemann, 1963). Differences in the z values between species occur. High heat resistance of an organism and high z values may be correlated (Hansen and Riemann, 1963). Despite the simplicity of logarithmic survivor curves,

Organism	Time (min.)	Temperature (°C)
Escherichia coli	20-30	57ª.
Pseudomonas aeruginosa	2	55 <sup>b</sup>
Staphlococcus aureus	19	60ª

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Table 3.3: Decimal reduction times for selected microorganisms.

a Source: Atlas and Bartha (1981)
b Source: Olson and Nottingham (1980)

Table 3.4: z values for selected micro-organisms.

Organism	(°C)	
Yeasts Most non-sporing bacteria	3 - 5 4 - 6	

Source: Hansen and Riemann (1963).

curves of other shapes are frequently observed (Figure 3.3). Curve A is the standard logarithmic curve. Curve B, with its lag in deaths, is frequently observed with clumped cells (Hansen and Riemann, 1963). Curve C is of particular concern because it seems to indicate that there is some temperature where the lethal effect of temperature is reduced (Haug, 1980).

Two theories have been advanced to explain the deviations from the logarithmic survivor curves. The "multiple target" theory was used by Moats (1971) to explain for thermal injury and death in bacteria. This theory could account for the lag period in curve C but not curve B.

Wei and Chang (1975) advanced a theory that random collisions between disinfectant molecules and microorganisms were the cause of microbial death. The probability for this collision was modeled with a Poisson distribution. Clumping of varying numbers of microorganisms lead to a multi-Poisson distribution model. The result was that organism clumping was the major reason for the different survival curves. The lag period of curve C was due to a high proportion of the population being present in clumps. Curve B was explained by a large proportion of non-clumping cells combined with a few large clumps.

The heat resistance of spores and vegetative bacterial cells increases with an increase in their growth temperature (Hansen and Riemann, 1963; Olson and Nottingham, 1980). Slow growing cells exhibit greater heat resistance than fast



TIME

Figure 3.3: Generalized types of survior curves observed in studies of heat inactivation of microorganisms (From Haug, 1980) growing cells (Hansen and Riemann, 1963). If large numbers of cells are initially present, longer times will be required to reduce the number of survivors to a given level (Olson and Nottingham, 1980).

Heated organisms may show an increased lag period before beginning their exponential growth phase (Lembke, 1937). This occurs even if the heat treatment did not kill large numbers of organisms (Kaufmann et al., 1959). Injured micro-organisms lose resistance to selective chemical agents including salts and antibiotics. Repair of sublethal damage to microorganims occurs more readily in simple than more complex media (Olson and Nottingham, 1980).

Bacteria, including E. coli, exhibit the lowest heat resistance during the exponential growth phase. The initial lag phase and the stationary phase have higher heat resistance (Hansen and Riemann, 1963; Olson and Nottingham, 1980).

Bacterial levels can continue to decline even after heat treatment stops and optimal growth conditions are restored (Jackson and Woodbine, 1962).

The heat resistance of microbial cells increases with decreasing humidity. Dry air at 140 to 150°C has less killing effect than wet steam at 100°C (Hansen and Riemann, 1963). Heat resistance of vegetative cells and spores can be increased in substances with relatively reduced water activity (Christian, 1980). This must be tested for each microbe and substrate combination, however (Olson and

Nottingham, 1980).

3.3.3.3: Moisture Content and Water Activity

Water must be available for micro-organisms to grow. A useful measurement of the availability is water activity  $(a_w)$ . Water activity can be changed by either reducing the amount of water or by adding solutes (Christian, 1980).

Water activity of a substance is the ratio of the water vapor pressure of the substance (p) to that of pure water  $(p_0)$  at the same temperature:

$$a_w = p / p_0 \tag{3.1}$$

. . . .

If a solution becomes more concentrated, the vapor pressure decreases and the  $a_w$  falls from the pure water value of 1.  $a_w$  values can be related to the equilibrium relative humidity (ERH) and osmotic pressure.

Ideally, water activity can be related to solute concentration using Raoult's law in the form

$$a_w = p / p_0 = n_2 / (n_1 + n_2)$$
 (3.2)

where  $n_1 = moles of solute$  $n_2 = moles of solvent$ 

Non-ideal behavior can result, however, either from reductions due to interaction between solutes or increases because of dissociation. Experimentally determined molal osmotic coefficients are used to compensate for this nonideal behavior (Christian, 1980). a<sub>w</sub> values can be calculated from

where v = number of ions generated by each moleculeof solute (v = 1 for nonelectrolytes) (3.3) m = molal concentration of solute $<math>\phi = molal osmotic coefficent$ 

Sources of information on the molalites for various solutes at a range of  $a_w$  values are available (Scott, 1957).

Despite the predictive value of the preceding equation for relatively simple solutions, for complex substrates it is more accurate to directly measure the relationship between water activity and moisture content. A number of factors that can influence vapor pressure and thus water activity include adsorption of water molecules onto surfaces and capillary forces, as well as solution concentration effects (Christian, 1980). Hysteresis is also present between drying and wetting moisture isotherms. At high  $a_w$ , micro-organism growth may be higher on the desorption isotherm than on the adsorption isotherm at the same  $a_w$ (Acott and Labuza, 1975). The effect of water activity on the growth of many species is largely independent of the solute that controls  $a_w$  (Scott, 1957).

Micro-organism growth is most rapid at  $a_w$  levels ranging from 0.995 to 0.980 (Christian, 1980; Atlas and Bartha, 1981). At lower  $a_w$ , growth rates and the stationary population decreases and the lag phase length increases. With sufficently low  $a_w$ , the lag phase becomes infinite (Scott, 1957).

Values of the limiting  $a_w$  for several selected organisms are shown in Table 3.5. Gram-negative bacteria, including Pseudomonas spp. and the Enterobacteriaceae only grow well above 0.96 and 0.93  $a_w$ , respectively. Gram-

positive non-spore-forming bacteria such as Staphylococcus aureus have a lower limit of 0.86  $a_w$ . Spore-forming bacteria can grow at  $a_w$  levels of 0.94 to 0.89, with the

Table 3.5: Approximate minimum levels of water activity permiting growth of micro-organisms at temperatures near optimal.

Organism	a <sub>w</sub>
Molds Aspergillus fumigatus	0.82
Bacteria Bacillus cereus B. stearothermophilus Enterobacter aerogenes Escherichia coli Psuedomonas fluorescens Salmonella sp. Staphylococcus aureus	0.95 0.93 0.94 0.95 0.97 0.95 0.86

Source: Troller and Christian (1978).

common limit being 0.90 to 0.91  $a_w$ . Fungi grow at much lower  $a_w$  than bacteria; fungal growth at high  $a_w$  levels is much slower than bacteria (Christian, 1980).

3.3.3.4: pH

The pH of a substance is an important factor in determining the survival and growth of bacteria in that substance. pH effects are difficult to separate from those of other effects such as the concentration of undissociated weak acids that are affected by pH (Corlett and Brown, 1980). The relative rate of proton leakage into the cell vs. the proton-rejecting capacity of the cell determines if an environment is inhibitory due to the activity of weak acids (Freese et al., 1973).

pH growth limits can vary among micro-organisms but most have optimum growth near pH 7 with ranges between pH 5 and 8. Minimum and maximum pH values for several selected micro-organisms are shown in Table 3.6.

Table 3.6: The limits of pH allowing initiation of growth by selected micro-organisms.

Organism	Minimum pH	Maximum pH
Gram-negative bacteria	<u> </u>	
Escherichia coli Klebsiella pneumoniae	4.4	9.0
(aerogenes)	4.4	9.0
Pseudomonas aeruginosa	5.6	8.0
Salmonella spp.	4.0	7.8-8.0
Gram-positive bacteria		
Bacillus cereus	4.9	9.3
B. stearothermophilus	5.2	9.2
Staphylococcus aureus	4.0	9.8
Streptococcus pyogenes	6.35	9.2

Source: Corlett and Brown (1980).

The heat resistance of bacteria is decreased by acid or alkaline conditions. The heat resistance generally has a rather narrow pH range outside of which resistance falls off quite rapidly. The optimum heat resistance typically occurs at pH between 6 and 8 (Hansen and Riemann, 1963; Corlett and Brown, 1980).

# 3.3.3.5: Redox Potential

Enzymatic reactions of micro-organisms are often oxidation-reduction reactions. Whether an organism can carry these redox reactions out depends on the redox state of the environment (Atlas and Bartha, 1981). Micro-organism such as strict aerobes or anaerobes which have only one terminal metabolic system are limited to a relatively narrow range of environmental redox potentials (Atlas and Bartha, 1981; Brown and Emberger, 1980). Facultive anaerobes have alternate systems which can be switched by either the environmental redox potential or oxygen concentration (Brown and Emberger, 1980).

Rapid decreases in redox potential have been associated with the early logarithmic phase of micro-organism growth (Hewitt, 1950), spore germination, and regrowth (Douglas et al., 1973).

# 3.3.3.6: Compost Microbial Ecology Studies

Finstein and Morris (1975) reviewed the microbiology of composting as it applied to solid waste. The density and succession of various micro-organisms as a function of temperature during composting has been studied by several authors (Waksman et al., 1939; Chang and Hudson, 1967; Stanek, 1972).

Bacteria are present in all stages of composting (Waksman et al., 1939; Chang and Hudson, 1967; Stanek, 1972; Finstein and Morris, 1975). Bacterial diversity decreases as temperature increases to inhibitory temperatures in the

thermophilic zone.

Actinomycete populations were slower to colonize fresh substrates than either bacteria or fungi (Lacey, 1973; Chang and Hudson, 1967). This was attributed to the ability of actinomycetes to degrade more complex substrates including cellulose, hemicellulose, chitin, and perhaps lignin (Lacey, 1973). Actinomycetes have been found to be more visible on dry vs. wet particles (Schultze, 1962), restricted to within 6 inches of the compost surface (Erickson, 1952), and to not grow well in poorly aerated masses of compost (Anon., 1953). Explicit studies of Actinomycete sucession during the temperature ascent are lacking (Finstein and Morris, 1975).

Different zones of temperature were noticed in the piles and fungi were active in the cool, dry exterior regions of the piles as compared with the hot interior (Chang and Hudson, 1967). High temperatures, acidity and anaerobic conditions were felt to limit fungal growth to the exterior of the compost pile (Kane and Mullins, 1973). Low pH values in stable manure composts were associated with slow decomposition rates and anaerobic conditions (Lambert and Davis, 1934).

Initially, large mesophilic and smaller thermophilic fungal populations were present (Chang and Hudson, 1967). Both populations fell, with the thermophilic fungal population disappearing after 5 days, and the mesophilic population disappearing after 5 to 8 days. A thermophilic population began to appear by day 8 and recovered to levels

of  $1 \times 10^7$  by approximately day 16. The mesophilic fungal population reappeared 20 to 34 days into the compost period and only recovered to levels of  $1 \times 10^3$  to  $1 \times 10^5$ .

The ratio of thermophilic to mesophilic fungi rose during composting, and high counts of thermophiles remained in areas that had cooled (Chang and Hudson, 1967).

After studying the biochemical changes that occurred during the experiment and the ability of fungi to utilize cellulose as a carbon source, Chang (1967) concluded that the ability to use complex carbon sources and the ability to thrive at high temperatures are the two important characteristics of successful colonizers of composts.

Waksman et al. (1939) studied substrate and microbial changes in stable manure held at four different constant temperatures for 47 days. The micro-organisms involved in the decomposition of the manure were found to have the following characteristics:

At 75°C, the animal population and the fungi were completely repressed. Actinomycetes appeared only seldom, at the surface of the compost. Only certain types of bacteria were active, belonging largely to the spore-forming, hemicellulose-decomposing types...

At 65°C, the bacteria and actinomycetes were chiefly concerned in the decomposition process. Fungi appeared only seldom, and animal forms were absent. The first two groups were represented by a number of characteristic thermophilic groups. After a certain period, the bacteria were gradually reduced and the actinomycetes became the predominant organisms. The thermophilic actinomycetes are limited to very few species, but comprised several genera.

At 50°C, certain thermophilic fungi were very active, in addition to the bacteria and actinomycetes. This selective population, in which fungi and actinomycetes played the predominant role, was responsible for the most rapid decomposition of the manure...The actinomycetes were similar to those developing at 65°C.

Lower temperatures, as typified by 28°C, gave rise to a highly heterogeneous population. Bacteria, fungi, actinomycetes, protozoa, and nematodes were well represented by a great variety of forms. A few days elapsed before certain active types became established, a fact which accounts for the delay in the rapidity of the decomposition process at this temperature.

Stanek (1972) summarized the knowledge about microbial

succession of mushroom compost as follows:

1. Number of micro-organisms growing at 25°C decreases during the fermentation process in compost; number of thermophilic and thermotolerant micro-organisms increases.

2. At first number of bacteria and then of actinomycetes and thermotolerant fungi increases. The dominant types of micro-organisms are:

(a) at the start of the fermentation process: mesophilic and thermotolerant spore-yielding and non-spore-yielding bacteria and quickly growing fungi (Phycomycetes--genus Mucor, etc.),

(b) during the period of the peak-fermentation process in the pile and during pasteurization: thermophilic actinomycetes (Streptomyces, Thermonospora spp.) and non-sporulating bacteria (Pseudomonas spp.),

(c) at the end of pasteurization: thermotolerent fungi (Humicola spp.etc.).

(3) The compost piles are colonized in various layers (Lambert and Davis, 1934) by various micro-organisms. This phenomenon is particularly striking before the first turning of piles: on the surface there appear bacteria and fungi (especially Phycomycetes) growing at a temperature of 25°C; in the layer where intensive aerobic processes occur grow thermophilic bacteria and actinomycetes; the centre of the pile is mostly colonized by anaerobic spore-forming bacteria (Clostridium spp. etc.). After turning the pile differences decrease by the homogenization of material.

(4) Various groups of micro-organisms take part in the decomposition of various substances. Some thermophilic actinomycetes and thermotolerant fungi decompose

cellulose, some of the thermotolerant bacteria, actinomycetes and fungi decompose pectin etc.

(5) The occurrence of individual kinds and groups of micro-organisms and their activity depend on the momentary conditions (humidity, aeration, etc.) and expecially on the quantity of accessible nutrients in the compost (C:N ratio, etc.: After adding glycides the number of bacteria had increased and the amount of the ammonium had decreased; by changing sources of nitrogen the ability of thermophilic actinomycetes and thermotolerant fungi to decompose cellulose also changed.

### 3.4: Biochemistry

### 3.4.1: Stoichiometry

Haug (1980) presented information on the general chemical composition of a variety of organic materials. Assuming an average compositon of sludge organics of  $C_{10}H_{19}O_{3}N$ , Haug determined the stoichiometric oxygen requirement.

 $C_{10}H_{19}O_{3}N + 12.5 O_{2} + 10 CO_{2} + 8 H_{2}O + NH_{3}$ Elevated temperatures and pH > 7.0 would lead to the volatilization of ammonia and Haug felt that nitrification oxygen demands would not normally need to be considered. Based on this assumption, about 2.0 g O<sub>2</sub> would be needed per gram of organic matter oxidized.

Finger (1975) took a slightly different approach using the following overall equation for compost reactions.  $(C_6H_{12}O_6)^n + WO_2 + d NH_3 + C_aH_bO_cN_d + Y CO_2 + Z H_20$ where a = 2.82n W = 3.03 n moles O2/mole subst. b = 4.69n Y = 3.18 n moles CO2/mole subst. c = 1.40n Z = 4.31 n moles H2O/mole subst. d = 0.436n

Finger based his stoichiometric equation on the assumptions that the substrate could be represented as a carbohydrate

macromolecule, that the elemental composition of the microbe is similar to yeast, and that the conversion efficiency of the substrate into cell material is 0.4 by weight.

The respiratory quotient (RQ) is the ratio of carbon dioxide produced to the oxygen utilized by microbes. The theoretical RQ for the complete oxidation of carbohydrates, protein and fats was given as 1.0, 0.8 and 0.7, respectively (Braithwaite, 1956). The RQ for forced aeration ground garbage composting was determined to average about 0.9 (Moore, 1958). Braithwaite (1956) found that the RQ was 1.0 or greater for the first few days and progressively lower for the remainder of the composting period, eventually approaching 0.6.

## 3.4.2: Compost Studies

Changes in a number of the biochemical constituents of compost or compost-like material have been studied by many authors. Gregory et al. (1963) carried out an extensive investigation on microbial and biochemical changes in moldy timothy and fescue grass hay. Gerrits et al. (1965) and Muller (1965) studied changes in biochemical constituents during the preparation of synthetic mushroom composts. Higgins et al. (1982) compared the organic composition of aerobic, anaerobic, and compost-stabilized sludges.

# 3.4.2.1: Organic Substrates

Chang (1967) analyzed changes in hemicellulose, cellulose, lignin, diastase and ethanol soluble fractions, total N and ammonium and nitrate N in wheat straw composts.

The straw lost over half of its dry weight after 60 days of composting; almost all of the loss occured in the first 34 days. The first 5 days had the greatest rate of loss with an average loss of 2.66 % per day as opposed to an average of only 1.3 % per day for the next 30 days. The ethanol soluble fraction, which contained sugars, glucosides, and essential oils showed a slight increase. Starch and glycogen were hydrolysed by diastase. This remained essentially constant over the composting period. Losses of hemicellulose and cellulose acounted for most of the total dry weight lost. Hemicellulose decreased from 35.6 to 16.9 percent. Cellulose changed from 45.3 to 13.2 percent. The rate of hemicellulose decomposition was uniform through the composting but cellulose decompositon rates varied. High cellulose decomposition rates were associated with thermophilic temperatures. Lignin did not change appreciably from approximately 10 percent.

Waksman et al. (1939) studied the influence of temperature upon the microbiological population and decomposition processes in horse manure composts. Manure was heated to four constant temperature levels for 47 days. Samples were withdrawn on the 9th, 19th, 33rd and 47th days for analysis of microbial populations, moisture, ash, ammonia, hemicellulose, cellulose, lignin, water soluble organic matter and water insoluble protein.

Total decomposition at 50°C was always greater than that at 28°C. The 75°C samples by far had the smallest

total decomposition. 65°C total decomposition was the highest at day 9 but by the 47th day it was approximately the same as the 28°C sample. The rate of cellulose decomposition was initially steeper than that of hemicellulose; the decomposition rates and levels became very similar by the end of the experiment. The effect of temperature on changes in cellulose content paralleled the order of the total decomposition rates. Almost no cellulose degradation occured at 75°C, however. Hemicellulose degradation was highest at 50°C and lowest at 75°C. Degradation of hemicellulose at 65°C was greater than that at 28°C. Increases in lignin contents were in the order of 28 > 50 > 65 >> 75°C. Protein content increases were ordered as 50 >> 65 = 28 >> 75°C. The results of Gerrits et al. (1965) largely confirm Waksman et al. (1939) results. **3.4.2.2:** Nitrogen Transformations

Initial accumulation of ammonia was inversely related to the rate of decomposition in fresh horse manure (Waksman et al., 1939). Whenever decomposition was delayed in the initial composting period, large nitrogen losses occurred. After 19 days the only traces of ammonia were found at 28°C and 50°C. Ammonia was present at 75°C for the entire experimental period, despite active volatilization due to high temperatures and alkaline conditions. Nitrate nitrogen began to appear in the 28°C and 50°C samples in 33 and 61 days, respectively. The 65°C samples had large accumulations of ammonia by the end of the experiment. Over the 61 day

experimental period, nitrate formation was greatest at 50°C followed by 28°C. Ammonia formation was greatest at 65 and 75°C.

Burrows (1951b) analyzed the changes in nitrogen, phosphorus, carbon/nitrogen ratios, and pH during composting and mushroom cropping. In a companion paper (Burrows (1951a), he described his methods of analysis and conducted an analysis of errors due to sampling and variance in measurements of total ash, acid insoluble ash, moisture, total nitrogen and calcium in the compost.

Burrows (1951b) found an increasing loss of nitrogen with nitrogen level without an increase in organic matter loss. Carbon/nitrogen ratios therefore narrowed during composting. Changes in pH occurring during the same time period indicated that ammonia volatilization was probably the cause of the nitrogen losses.

Temperature was found to have a marked independent effect on nitrogen losses (Burrows, 1951b). Nitrogen losses plotted against the mean maximum temperature between turns indicate that stack losses are quite high at 70°C but almost negligible at 60°C.

The retention of several nitrogen sources in a compost pile was evaluated (Burrows, 1951b). Differences between sources was highly significant with urea showing the greatest losses.

Burrows speculated on the results of this experiment: ... Previous work, confirmed by the present

investigation, shows that a higher nitrogen content tends to increase the rate of formation of ammonia but a higher carbon-nitrogen ratio enable the ammonia formed to be reassimilated rapidly by organisms growing on the abundance of carbohydrate. The temperature effect may operate in two ways: first, by affecting the rate of bacterial transformation of proteins into ammonia. According to Waksman the rate appears to increase with rising temperature until an optimum in the region of 65°C is attained, when the rate decreases, no doubt owing to the adverse effect of the higher temperature upon the bacterial population. Secondly, a rise in temperature will cause a more rapid removal of ammonia, by physical agencies, from the neighbourhood of the growing bacteria in the compost heap, thus increasing nitrogen losses as the temperature rises.

Low nitrogen composts had very high initial immobilization of ammonia (Beckwith and Parsons, 1980). Two thirds of the ammonia and half of the nitrate was mineralized and immobilized, respectively, in low nitrogen composts. All inorganic nitrogen was immobilized by day 10. The maximum incorporation of nitrogen into the organic nitrogen fraction occurred by the 20th day. Ammino acids showed similar patterns to the organic nitrogen values and were essentially constant after day 10. Amino sugars first appeared on day 10; maximum levels occurred on day 20 and 30 for the low and high nitrogen composts.

Recovery of added fertilizer was highest in the low nitrogen (94 %) as opposed to the high nitrogen (88 %) compost (Beckwith and Parsons, 1980). In the initial stages of decomposition, there was a large increase in biomass. As activity declined, dead cells and cell contents provided a carbon source.

Suzuki and Kumada (1977) concluded that nitrogen

transformation during the rotting process of rice straw compost involved ammonification followed by the simultaneous occurrance of nitrification and denitrification and finally nitrification. A spatial pattern of nitrogen transformation was also evident: the outermost layer underwent nitrification, the interior ammonification, and the intermediate layer had both processes occurring.

# 3.4.2.3: Effect of Carbon Source

The availability of the carbon source to microorganisms in the composting process is as important as the nitrogen source. Mote and Griffis (1980) composted three different mixtures of materials with different carbon sources. Bulk densities and amounts of nitrogen, water, and carbon were held the same. Each compost exhibited different combinations of three composting rates.

Gerrits et al. (1965) found that the addition of amendments to horse manure compost that had high levels of readily available carbon caused rapid increases in compost temperatures. Amendments with the same nitrogen levels but less readily available carbon showed smaller increases. 3.4.2.4: Effect of Inorganic Materials

Bretzloff and Fluegel (1962) studied the changes in several inorganic chemical constituents in a mushroom compost pile made of manure, corn cobs, hay and other supplements over a 30 day period. Moisture content, conductivity, pH, total nitrogen, Kjeldahl nitrogen, phosphorus, potassium, calcium, magnesium, sodium and

several ash fractions were determined from 9 locations along a compost windrow. Temperature and oxygen contents were measured at the same locations. The pile was turned 5 times during the 30 day composting period.

Moisture content started at 52 % wb and increased to 72 % wb in 10 days, after which it leveled off for the remainder of the composting period (Bretzloff and Fluegel, 1962). Total ash content showed an initial jump from 20 to 25 % after the first 8 days and a linear increase to 35 % by the end of the 30th day. Acid-insoluble ash increased linearly from 10 % to 18 % over the composting period. pH showed an initial increase from 7.0 to 7.6 and an approximately linear decrease to 7.0 by the end of the composting period. The nitrogen, total phosphorus, calcium and magnesium increased during composting. Potassium and sodium contents were quite variable but showed small increases.

Mineral amendments (bentonite, kaolinite and finely ground calcined aluminium oxide and ferric oxide) had little effect on the rate of decomposition in low nitrogen synthetic composts (Beckwith and Parsons, 1980). Kaolinite and bentonite produced a small accumulation of organic material on high nitrogen synthetic composts.

The addition of ground gypsum improves aeration, water movement and drainage in composting due to flocculating action on the colloidal compost materials (Pizer, 1950).

### 3.5: Empirical Studies

#### 3.5.1: Temperature

Bartholomew and Norman (1953) carried out a series of experiments to study the influence of initial temperature on the rate of heat evolution. Decomposing straw was tested under adiabatic conditions at three separate initial temperatures. Lower initial temperatures had prolonged incubation periods. Maximum hourly temperature increments occurred when the temperature had risen 4 to 8°C above the starting temperature.

McKinley and Vestal (1984) found that the maximal respiration for sewage sludge composting occurred in the range of 35 C to 45°C. Other studies have noted the temperature optimum for composting was in the range of 50 to 55°C (Finstein et al., 1980).

### 3.5.2: Oxygen and Carbon Dioxide

Oxygen and carbon dioxide concentrations were measured in mushroom compost windrows (Lambert and Davis, 1934). Haug (1980) summarized data on oxygen uptake as a function of temperature (Figure 3.4).

### 3.5.3: Moisture Content

Vigorous heating of a variety of substrates up to temperatures of 55 to 60°C when gravimetric moisture contents are between 40 to 60 % wb has been reported by James et al. (1928). Schultze (1961), Jeris and Regan (1973b) and Snell (1957) studied the relationship between oxygen uptake and the wet basis moisture content in



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Figure 3.4: Observed oxygen consumption rates for various composting mixtures and reactor types as a funciton of temperature. Each curve represents the best fit of observed data (From Haug, 1980)

substrates of rewetted compost, refuse and ground garbage, respectively. This was summarized by Haug (1980) as shown in Figure 3.5. Below about 50 % wb moisture content negatively affected oxygen uptake to the point where at 20 % wb almost no biological activity occurred (Glathe, 1960). Between 50 and 70 % wb, oxygen uptake rates were at their maximum; rates began to decrease at higher moisture contents.

Haug (1980) indicates that low moisture contents can lower the rates of reaction because the bacteria that cause the composting action require an aqueous environment, and mass transport limitations for soluble components may be encountered under low-moisture conditions. Haug (1980) also notes the difficulty in isolating effects of moisture alone because of the relationships between moisture, bulk weight and FAS.

Bartholomew and Norman (1953) studied the effect of initial moisture content on the temperature rise of decomposing straw under adiabatic conditions using forced aeration. The experiments were started at 25°C and a range of moisture contents (% db) from 75 to 275 % were examined. In the mesophilic range, the time-temperature profiles were similar; deviations were noticed in the thermophilic range. Microbiological activity was highest at higher moisture contents, as measured by heat production and decomposition.

Increases in average moisture content in a naturally ventilated horse manure compost windrow lead to increases in


the carbon dioxide content at locations in the windrow (Gerrits, 1972). Very wet composts using the same substrate exhibited slower temperature rises and higher maximum temperatures than drier mixtures. These trends were attributed to delays in microbial activity and the larger thermal mass present in the wetter compost, respectively. Moisture contents of between 70 to 72 % wb were associated with aerobic  $(5-20 \ \ 0_2)$  and micro-aerophilic  $(0-5 \ \ 0_2)$ conditions in the largest part of the heap. Observations of lower moisture content (68 %) composts indicated that they were heavily aerated with cold air. Temperatures were observed to be lower and decreased quickly after maximum temperatures were reached. Gerrits (1972) concluded that approximately 75 % of the heat generated through the combustion of dry matter by micro-organisms is used for evaporation.

Some substrates, such as cotton gin trash dry out very quickly and need intensive water management if decomposition is to proceed in a rapid manner (Mote and Griffis, 1980).

#### 3.5.4: Windrow Size

Size reduction in a domestic refuse windrow from 10 ft x 20 ft to 5 ft x 13 ft improved natural aeration at the expense of increased heat loss (Horstmann and Ehgelhorn, 1969). Strom et al. (1980) recommended a leaf composting strategy that utilized small piles in the fall to promote aeration. Two of the small piles were combined into one larger windrow in the winter to retain heat. Proportions of

the compost subject to acid, anaerobic and non-reactive zones increased with the height and width of the windrow (Lambert and Davis, 1934).

## 3.5.5: Windrow Zones

Lambert (1941) presented a detailed description of different zones commonly encountered in mushroom compost heaps (Figure 3.6). The patterns in physical conditions were dependent on the size, shape and compactness of the windrow and changed over time. Zone A is an outside layer



Figure 3.6: Section through a mushroom compost heap illustrating the typical differences in temperature and aeration (From Lambert, 1941).

that has temperatures varying from ambient temperatures to 43°C. This zone is well aerated. The sides can become very dry due to excessive aeration and the top wet in wet or cool weather. Zone B is moderately moist, well aerated and has temperatures from 43 to 60°C. The third zone, C, extends like a huge doughnut around the windrow 2 to 4 feet from the sides and 3 feet from the top. The highest temperatures are found in this zone: 60 to 82°C. The fourth zone (D) is anaerobic and occupies the entire lower central part of the windrow.

#### 3.6: Kinetic Modeling

## 3.6.1: Microbial Growth

Whang and Meenaghan (1980) developed a kinetic model of the composting process. They assumed that enzyme kinetic concepts were applicable to the development of the composting model, that an intermediate complex of microorganisms and substrate was formed under a quasi-equilibrium state and that endogenous reaction is irreversible. An equation similar to the Michaelis-Menten equation was derived:

R	=	K <sub>2</sub>	(C)	1	(K1	+	(C))	(3.4	)

where	R	=	consumption of substrate
	K <sub>1</sub>	=	$(k_1 + k_2) / k_1$
	K2	2	$k_{2}(X_{T})$
	Ĉ	-	substrate
	ΧŢ	=	total micro-organism concentration
	•	=	X + CX*
	Х	Ξ	free micro-organism
	CX*	=	activated substrate-organism complex
k <sub>1</sub> , k_	1, <sup>k</sup> 2	=	specific reaction rates

Values of Kl and K2 were determined from an experimental compost reactor using humidified forced aeration with daily turning in a batch mode.

Haug (1980) discussed the general sequence of events in the catabolism of solid substrate by composting microorganisms. Some of the steps included:

1. Release of extracellular hydrolytic enzymes by the

cell and transport of the enzymes to the surface of the substrate: 2. Hydrolysis of substrate molecules into lower molecular weight, soluble fractions; 3. Diffusion transport of solubilized substrate molecules to the cell; 4. Diffusion transport of substrate into the microbial cell, floc or mycelia; 5. Bulk transport of oxygen (usually in air) through voids between particles; 6. Transport of oxygen across the gas-liquid interface and the unmixed regions which lie on either side of such an interface: 7. Diffusion transport of oxygen through the liquid region: 8. Diffusion transport of oxygen into the microbial cell, floc or mycelia; and 9. Aerobic oxidation of the substrate by biochemical reaction within the organism. Haug (1980) presented a derivation of the substrate

consumption and microbial growth equations based on single substrate limitations. A form of the Monod equation was used. Microbial growth can be related to substrate use by the equation:

$$dX / dt = Y_m(-dS/dt) - k_e X \qquad (3.5)$$

where dX/dt = net growth rate of microbes, mass/volumetime  $Y_m$  = growth yield coefficient, mass of microbes/mass of substrate k<sub>e</sub> = endogenous respiration coefficient, l/time or mass of microbes respired/mass of of microbes-time concentration of microbes, mass/volume X = = maximum utilization coefficient, maximum km rate of substrate utilization at high substrate concentration, mass substrate/mass microbes-day

Under substrate limiting conditions the combined growth equation can be derived:

$$dX/dt = Y_m (k_m SX/(K_s + S)) - k_p X$$
 (3.6)

 $(dx/dt)/X = Y_m k_m S/(K_s + S) - k_e$  (3.7)

where (dX/dt)/X = net specific growth rate

or

S = concentration of rate limiting substrate, mass/volume

The four kinetic coefficients,  $Y_m$ ,  $k_m$ ,  $K_s$  and  $k_e$  need to be known for a specific substrate and microbe combination. Haug (1980) presents data on a range of biological processes.

Sinclair and Ryder (1975) compared the ability of two different growth models to explain continuous culture data under both carbon and oxygen limiting conditions. The interacting substrate model postulates an interaction between two substrates and is based on double enzyme kinetics. Only one of two substrates would enter into the model at any one time in the alternate substrate model. Both Monod/Monod and Monod/Contois expressions worked well in both models. The models were able to satisfactorily explain experimental results.

## 3.6.2: Microbial Death

If

Haug (1980) developed a first-order decay model for inactivation kinetics which is often refered to as "Chick's Law." The most common form is given as

 $n_{t} = n_{0} exp(-k_{d}t)$ (3.9)

 $n_0 = initial cell population$ where

 $n_{+}$  = later population at time t

The temperature effect on  $k_d$  is typically modeled by the Arrhenius form

 $k_d = C \exp(-E_d/RT_k)$ (3.10)

where C = constant  $E_d$  = inactivation energy, kcal/mole  $T_k$  = temperature, K

Inactivation energies for many spores and vegetative cells range between 50 and 100 kcal/mol (Bailey and Ollis, 1977). By taking the logarithim of the above equation, a plot of the log of  $k_d$  vs.  $1/T_k$  from survivor plot data can be used to find C and  $E_d$  (Haug, 1980).

Since the temperature of the compost changes with time,  $k_d$  will not be constant. Combining Equations (3.8) and (3.10) gives

 $dn / dt = -C n \exp[-E_d / RT_k(t)]_n$  (3.11)

where  $T_k$  is a function of time,  $T_k(t)$ . This expression can be used to evaluate the kill resulting from various timetemperature profiles by separating the variables and integrating from the intial to the final conditions:

$$\ln(n_0/n_f) = \begin{array}{c} t_f \\ c \exp \left[-E_d/RT_k(t)\right] dt \quad (3.12) \\ t_0 \end{array}$$

where the subscript o indicates initial and f final conditions. Haug (1980) noted that integrations for hyperbolic, exponential and linear time-temperature functions have been performed, in particular by Bailey and Ollis (1977). In composting situations, the timetemperature curves may not follow profiles for which analytical solutions are available. Graphical (Haug, 1980) or numerical procedures could be used to calculate microbial death due to temperatures in those cases.

Large clumps of compost particles have been observed to form during composting. Haug (1980) examined the effect of this solids clumping on microbial destruction. He assumed a spherical homogeneous ball of compost material heated from the outside and thermal and physical properties based on those for water and compost. Using these assumptions he calculated the length of time that it would take for the interior of clumps of various sizes to heat to 0.90 times the ambient temperature. Heating times for particles of between 1 and 10 cm radius were found to be negligible; only when clumps were greater than 20 cm radius did heating times become significant.

Nonuniform temperature distributions can affect the overall thermal deactivation of pathogens. The effects of these nonuniformities have been examined for windrow (Haug, 1980) and static pile systems (Haug, 1980; Burge et al., 1978). For windrow systems, thermal inactivation can be described as:

$$n_t = n_0 [f_1 + f_h exp(-k_d \Delta t)]^N \qquad (3.13)$$

and

$$f_1 + f_h = 1$$
 (3.14)

where nt = number of organisms surviving no = number of organisms initially present f1 = fraction of composting material in the lowtemperature, sublethal zone fh = fraction of composting material in the hightemperature zone At = time interval between pile turnings

- $k_d$  = thermal death coefficient
- N = number of pile turnings

Two different  $f_1/f_h$  values and several  $k_d \Delta t$  values were evaluated. The fraction of surviving organisms was much greater than that calculated by examining a specific timetemperature curve. Haug (1980) notes that this indicates that the exposure of all portions of a windrow to lethal temperatures is as important as achieving time-temperature curves at any one location in order to increase the average thermal inactivation.

Furthermore, the above analysis is based on the assumption that all particles are randomly mixed during the turning process. As Haug notes, this may be true if commercial turning devices are used. If a front-end loader is used, however, complete mixing will probably not occur. The loader can be used, however, to place portions of the windrow that need additional heat treatment in zones that should receive higher temperatures. If only a small portion of material on the outside of the pile comprising 1 % of the total compost mass escapes mixing, the average thermal inactivation would be limited to no more than 3  $D_r$  (Haug, 1980).

Burge et al. (1978) measured the temperature distributions in 15 static piles of sewage sludge and wood chips using forced aeration and used this data to predict the confidence levels for achieving a particular timetemperature relationship. The number of days that different

	Con	fidence Levels	; (%)
Cemperature	95 (Davs)	99 (Dave)	99.9 (Davs)
	(Days)	(Days)	(Days)
>50	13.8	13.3	12.6
>55	10.6	10.1	9.4
>60	7.3	6.8	6.3
>65	4.3	3.9	3.4
>70	1.2	1.0	0.8

Table 3.7: Confidence levels that all material will obtain a temperature equal to or greater than a particular temperature for a desired number of days.

temperatures could be reached are shown in Table 3.7.

Burge et al. (1978) also examined the mean and standard deviation of temperature in the toe area of the 15 test piles. Examining the data, Haug (1980) notes that

Significant reduction of bacteriophage f2 would be predicted not only on the basis of the mean temperature but also the temperature obtained by subtracting the standard deviation from the mean.

The confidence levels shown in Table 3.7 apply only to the 15 test piles as they will vary with the substrate material, bulking agent and manner of operation (Haug, 1980).

3.6.3: Regrowth

Coliform and fecal streptococcus bacteria have been observed to regrow in sterile liquid sludge heated to 35°C (Brandon, 1878). The most dramatic regrowth of fecal streptococcus bacteria was observed in sterilized material that was then recontaminated (Ward and Brandon, 1977). Occaisional regrowth of coliform organisms was observed during windrow composting of sewage sludge, particularly in wet winter (California) conditions (Selna and Smith, 1976).

### 3.6.4: Combined Equations

Haug (1980) proposed a net rate coefficient equation based on empirical expressions from experimental data to describe the overall kinetics of sewage sludge composting:

 $k_d = (F1)(F2)(FO_2)k_{dm}$  (3.15)

where

F2	=	free air	space	correction	
0_	Ŧ	OXVGAD CO	ntent	correction	

Fl = moisture content correction

FO<sub>2</sub> = oxygen content correction
kdm = maximum rate coefficient determined by
substrate and temperature conditions

Haug assumed that the oxidation of biodegradable volatile solids (BVS) is first-order with respect to BVS quantity:

$$d(BVS) / dt = -k_d(BVS)$$
 (3.16)

The distinction between BVS and nonbiodegradable volatile solids is made to distiguish between materials that are readily degradable and those that take longer to degrade (Haug, 1980).

Haug assumed that the rate constant  $k_d$  was a function of temperature only. Based on studies of garbage composting by Schultze (1962) that determined oxygen consumption, Haug (1980) developed the following empirical equation:

$$k_d = 0.00632 (1.066)^{T-20}$$
 (3.17)

Where T is in degrees Celsius and  $k_d$  (g BVS oxidized/g TVS-day).

Heat inactivation due to increased temperatures was accounted for in Haug's models using an expression developed by Andrews and Kubhu (1973) to describe similar effects during aerobic digestion of liquid wastes:

 $k_{d} = k_{dR1} [C_{1}^{(T-TR1)} - C_{2}^{(T-TR2)}]$ (3.18) where  $k_{dR1} =$  rate constant at temperature  $T_{R1}$ ,  $day^{-1}$  $C_{1}, C_{2} =$  temperature coefficients  $T_{R1}, T_{R2} =$  reference temperatures, C

Equations 3.17 and 3.18 were combined and reasonable values were assumed to arrive at the effect of temperature on  $k_d$  (Haug, 1980):

 $k_{dm} = 0.0126 [1.066^{(T-20)} - 1.21^{(T-60)}]$  (3.19)

The effect of moisture content on oxygen consumption rates and rate of BVS oxidation was estimated with data from Schultze (1962), Jeris and Regan (1973b) and Snell (1957). An "S" shaped curve was fit to the data by two equations for different moisture content ranges.

The effect of low free air space (FAS) on oxygen transport was modeled by Haug (1980) using data from Jeris and Regan (1973b) for refuse compost. Thirty percent was the optimum FAS in terms of oxygen uptake rates. Two separate equations covering the range of FAS values were fit to the data. FAS effects were considered to be important only for those composting systems that did not use bulking agents. As long as some FAS was present, Haug (1980) felt that it would have a negligible effect on reaction kinetics. Knowledge of the bulk weight of the compost material was necessary to calculate the FAS.

Oxygen content effects on compost reaction kinetics were felt to be very complex by Haug. The effect of free air space oxygen concentration was assumed to follow a Monod-type expression:

 $FO_2$  = VOLPO2 / (VOLPO2 + 1.0) (3.20) where VOLPO2 is the volume percent oxygen in the FAS. The effect of oxygen concentrations above 5 % were minimized by the assumption of a half-velocity constant of 1.0.

3.7: Physical Properties

#### 3.7.1: Particle Size

Chang and Rible (1975) analyzed fresh, deposited and composted livestock wastes to determine their particle size distribution and to characterize each size fraction in terms of its value as fertilzer, feed suplement and fuel. Composted dairy wastes showed a higher concentration of large fibrous materials than fresh waste. Moisture contents of larger size fractions remained the same while smaller sized particles showed large decreases. Crude fiber and protein decreased by nearly 50 % in most size fractions. Fat content decreased in all particle sizes. Ash contents increased by 75 to 100 percent.

Mears et al. (1975) analyzed the particle size of a number of different compost mixtures. They had problems with measuring the particle size of material with greater than 45 % wb. The method of drying affected the particle size determinations for this material. Particle size measurement of material that was initially drier than 45 % wb was not affected by drying method. Particle size followed a log normal distribution. Geometric mean diameter was

determined for each windrow on a weekly basis and decreased over time. The rate of decrease varied between the substrate mixtures and the reported work did not consist of sufficent experimental windrows to draw conclusions about any one substrate.

## 3.7.2: Particle Density

Chen (1982) reported mean values of beef cattle manure dried solids density of 1524 kg/m<sup>3</sup>. The average mean particle density of dairy manure solids obtained from three separate farms was 1551 kg/m<sup>3</sup> (Bohnhoff and Converse, 1986a). Regardless of the source, composted material had mean particle densities that were significantly greater than the mean particle density of freshly separated solids.

Bohnhoff et al. (1984) and Bohnhoff and Converse (1986a) present two equations for determining particle density. The earlier equation is a totally empirical linear regression on volatile solids. The later equation is derived from the definition of mean dry particle density with terms for the densities of volatile and fixed solids obtained by nonlinear least squares regression.

#### 3.7.3: Bulk Density

Mixtures of swine waste and refuse were initially between 275 and 500 kg/m<sup>3</sup> and increased to between 650 and 850 kg/m<sup>3</sup> after 27 days of composting (Mears et al., 1975). 3.7.4: Derived quantities

When bulk density, particle density and gravimetric moisture content are known a number of other quantities can

be calculated (Hillel, 1982). These include the porosity (f), void ratio ( $\epsilon$ ), volumetric moisture content ( $\theta$ ), degree of saturation (s) and air filled porosity ( $f_a$ ) or free air space (FAS).

#### 3.7.5: Compressibility

Based on a method developed for evaluating silage materials, Mears et al. (1975) determined the compressibility of swine waste based compost materials. They found that a relationship between bulk density,  $\rho_{\rm b}$ , and applied axial stress,  $\sigma$ , adequately described the compressive properties of the composted materials:

 $\ln \sigma = \ln \sigma_0 + C \ln \rho \qquad (3.21)$ where ln  $\sigma_0$  and C are regression coefficients formed by the statistical analysis of the data.

#### 3.7.6: Settlement Behavior

Stentiford et al. (1984) reported changes in 1.7 m tall triangular windrow cross-sections for mixed refuse composting by the static pile method. The maximum change in the pile height came in the first 5 days with 60 percent of the 36 cm total decrease.

Mears et al. (1975) measured windrow volume reductions in swine waste based windrow composts. Reduction in windrows composed entirely of swine waste ranged from 8 to 16 % after 10 days and 23 to 45 % in 40 days. A mixture of swine waste and straw had a reduction of 28 % after 50 days.

The time-settlement behavior of milled urban refuse under saturated conditions has been studied by Chen et al. (1977). A mathematical model for solid waste settlement was developed by Zimmerman et al. (1977). It consists of two simultaneous equations, one of which is non-linear. The effects of finite strain, biological and chemical activity, and the time variation of saturation have been included.

#### 3.8: Heat Transfer

#### 3.8.1: Diffusion

#### 3.8.1.1: Thermal Conductivity

Thermal conductivity is a basic heat transfer property of a material. Materials can be considered conductors (high conductivity, high heat transfer) or insulators (low conductivity, low heat transfer). The material in question can consist of a single phase (ie. gas, liquid or solid) or can be a combination of phases. Each phase can consist of a mixture of materials, as well.

Heat conduction in gases, vapors and liquids depends largely on the molecular transfer of the kinetic energy of molecular movement (Karak and Yener, 1979). Temperature and pressure have an important influence on the thermal conductivity of these substances. Liquids with their closer molecular spacing have much higher thermal conductivities than gases.

Thermal conductivties of mixed state materials are affected by the properties of each state and the way in which they are combined. Based on the structure of the solid state, materials can be classified as fibrous (textiles, fiberglass wool, straw), granular (powders, coal,

grain) or cellular (cork, foam insulating boards). Factors affecting thermal conductivity of such material include the (1) conductivity of the component material, (2) pressure of interstitial fluid, (3) temperature, (4) bulk density, (5) particle size, (6) particle size distribution, (7) void space and porosity, and (8) moisture content (Chun-Yung Chen, 1969).

Simple models of thermal conductivity relate the porosity and conductivity of the two phases as separate resistances arranged in series and parallel (Pratt, 1969). Other theoretical models are based on the porous material having a continuous solid or continuous air phase (Hillel, 1981).

Pratt (1969) presented experimental data showing the variation in effective thermal conductivity due to the presence of different gases in a fibrous insulation. Helium containing insulation had five time the thermal conductivity of air while the thermal conductivity of insulation filled with  $CO_2$  was only 72 % of air. The thermal conductivity of the solids in the matrix has a direct effect on the effective thermal conductivity.

Temperature changes effect the apparent conductivity through two mechanisms: the thermal conductivities of the components and the contribution of radiation (Chen-Yung Chen, 1969). Thermal conductivities of gases increase with temperature. Some liquids, such as water, show the same trend.

In addition to the purely conductive effects, actual

heat transfer in heterogenous materials can be by convection or radiation as well as by conduction. Depending on the method or scale of measurement, these transfer modes are sometimes included in an apparent or effective thermal conductivity. At typical composting temperatures, the radiation effects are minute.

Increases of fibrous material bulk density increase thermal conductivity. Pratt (1969) observed that many researchers have shown that the thermal conductivity in low bulk density fabrics with porosities of about 90 percent are almost independent of the component fiber. Allcut (1951) performed a series of measurements of apparent thermal conductivity for various material and densities. A characteristic hook shape is shown in all thermal conductivity curves (Figure 3.7). The cause for this shape is heat transmission by convection. Increasing densities



Figure 3.7: "Apparent" thermal conductivity of various materials at different densities. A, kapock; B, baggasse; C, cork board; D, slag wool; E, mineral wool (From Pratt, 1969).

reduce the convection heat transfer contribution to the apparent thermal conductivity by dividing the air layers into smaller layers, thus increasing the medium's tortuosity and increasing it's resistance to fluid flow.

After a certain density is reached, however, the apparent thermal conductivity begins to increase. The exact density varies between materials and is dependent on, among other things, the ratio  $K_s/K_q$  of the solid to the gas thermal conductivity. Deissler and Boeqli (1958) found that the effective conductivity of a void was strongly influenced by material arrangement for high  $K_s/K_q$ . Chun-Yung Chen (1969) visualized this as being due to the contact point between the solid particles. Gas is a relative insulator in high  $K_s/K_q$  systems, so most heat flow takes place near the contact points. For values of  $K_s/K_q$  of approximately 1000, nearly all the heat transfer takes place near the point of contact (Deissler and Boegli, 1958). Changes in bulk density increase the number of contact points, leading to greater contributions of conductive heat transfer to the overall apparent thermal conductivity.

A bulk material contains two types of gas spaces: intra- and inter-particle. If the gas has a lower thermal conductivity than that of the solid, intra-partical gas lowers the particle effective conductivity. The cells can be large or small, closed or open. Closed cell material voids are essentially air and vapor tight, while open cell voids are interconnecting and permit free movement of air

and vapor through the material (Pratt, 1969).

The effect of inter-particle gas space on the effective thermal conductivity depends on the characteristics of the system. At very low bulk densities, with large porosities and pore sizes, convective heat transfer is large and important. As overall porosity and pore size decrease, convective heat transfer decreases. This leads to a decrease in the effective thermal conductivity. It is important to note that decreases in pores sized can also lower thermal conductivity by increasing the tortuosity and resistance to convective heat transfer (Verschoor and Greeber, 1952).

The influence of latent heat transfer by water vapor in air-filled pores can be significant (Hillel, 1981; Pratt, 1969). Latent heat transfer effects can be taken into account by the additon of an apparent conductivity due to the evaporation, transport, and condensation of water vapor to the thermal conductivity of air (Hillel, 1981). This value is strongly temperature dependent and rises rapidly with increasing temperature (Figure 3.8). At about 55 to 60°C it is approximately the same value as the thermal conductivity of liquid water (Pratt, 1969).

Mears et al. (1975) calculated thermal conductivity for composts consisting primarily of swine wastes from previously determined values of thermal diffusivity, bulk density and specific heat:



Figure 3.8: Effective conductivity of porous material due to latent heat transfered by movement of water vapor (From Pratt 1969).

$$K = 0.1163 \alpha \rho C_{p}$$
 (3.22)

Statistical analysis of the data indicated that thermal conductivity varied linearly with moisture content. Thermal conductivity at any given moisture content increased significantly as the compost matured.

Houkom et al. (1974) and Chen (1983) measured the thermal conductivity of beef cattle manure. Chen developed three separate regression equations for different manures that related thermal conductivity to bulk density, total solids and porosity.

Bohnhoff and Converse (1986a) measured the thermal conductivity of dairy manure solids at 2 different moisture contents, three temperatures and three bulk densities. A four parameter equation relating thermal conductivity to temperature and volumetric moisture content was selected.

## 3.8.1.2: Specific Heat

Specific heat has been found to vary linearly with the wet basis moisture content for swine waste (Mears et al, 1975) beef cattle manure (Houkom et al., 1972; Chen ,1982) and separated dairy manure solids (Bohnhoff and Converse, 1986a).

## 3.8.1.3: Thermal Diffusivity

The thermal diffusivity of a swine waste compost was determined by Mears et al. (1975) using the transient method. Thermal diffusivity of dairy manure solids was calculated by Bohnhoff and Converse (1986a).

### 3.8.2: Natural Convection

Principles of convection through porous media are discussed by Bejan (1984). Haug (1980) developed a simple natural convection model to assess the ability of this process to supply oxygen at stoichiometric rates.

#### 3.9: Mass Transfer

The spatial scale in a composting system is associated with different types of mass transfer processes. Gas and vapor transfer in windrow voids could occur by diffusion or natural convection. Liquid transfer in void spaces could occur due to saturated or unsaturated flow. Gas transfer from the free air space across the liquid film to the substrate-microbe complex is by diffusion.

## 3.9.1: Windrow Void Space Transfer

### 3.9.1.1: Diffusion

Experimentally determined values of diffusion coefficients in gases at one atmosphere are shown in Table 3.8. The binary diffusion of gases can be predicted for given temperatures and pressures using the Chapman-Enskog kinetic theory or empirical correlations (Cussler, 1984). The Chapman-Enskog theory assumes nonpolar gases and this excludes water and ammonia (Cussler, 1984). Diffusion of gases vary with the 1.5 to 1.8 power of temperature (Cussler, 1984).

Table 3.8:	Experimental	values of	diffusion	coefficients	in
	gases at one	atmosphere	2.		

Gas Pair	Temperature (°K)	Diffusion Coeficient (cm <sup>2</sup> sec <sup>-1</sup> )
AirCO <sub>2</sub> AirO <sub>2</sub> AirH <sub>2</sub> O	276.2 273.0 289.1 298.2	0.142 0.1775 0.282 0.260
	333.2	0.3050

Source: Cussler (1984).

Shell (1955) studied the diffusion rate of oxygen through a ground garbage compost. The relative diffusion rates were shown to be linearly related to the free air space of the material. Increases in moisture content decreased the relative oxygen diffusion rate. Increases in

bulk density decrease the relative diffusion rate.

Hillel (1981) discussed a number of experimental efforts to relate the diffusion of gases in soils to the diffusion rate in air and derived a general equation for transient diffusion in the soil.

Equimolar counterdiffusion occurs when the same number of moles of two gases in separate reservoirs diffuse towards one another (Geankopolis, 1983). Finger (1975) assumed that the equimolar counterdiffusion of oxygen and carbon dioxide accounted for mass transfer in his distributed heat and mass transfer model of a compost pile.

Diffusion in many systems involves more than one component. In composting systems, observations of steaming indicate that water should be considered in addition to oxygen and carbon dioxide. Multicomponent diffusion is estimated by converting the problem to a binary problem, solving it and then converting back to a multicomponent solution (Cussler, 1984).

Diffusion of gases in porous solids and capillaries is discussed by Geankopolis (1983) under Fickian, Knudsen and transition regimes. Isothermal diffusivity of water vapor with respect to soil volumetric moisture content was derived by Jackson (1964).

## 3.9.1.2: Evaporation

The drying rate of biological products with initial moisture contents above 70 to 75 % wb can be constant if external drying parameters such as air velocity, air

temperature and air humidity are constant (Brooker et al., 1981). Constant rate drying will be observed under constant external conditions when the internal resistance to moisture transport is much less than the external resistance to water vapor removal from the surface of the product (Brooker et al., 1981).

Brooker et al. (1981) presents an expression for the constant rate moisture loss for biological products. The surface area and either the heat or mass transfer coefficents must be known for the constant drying rate to be calculated.

Bohnhoff and Converse (1986b) developed desorption isotherms for water desorption equilibria at five temperature levels. Three isotherm models were fit to the data; the relationship between moisture content, relative humidity and temperature was best described by the four parameter Chen-Clayton equation.

Equations for estimating the isosteric and integral heats of desorption over a temperature range of 0 to 70°C were also developed (Bohnhoff and Converse, 1986b).

#### 3.9.1.3: Liquids

Hillel (1981) discusses the concept of hydraulic diffusivity to describe the convective transport of water in soil pores. Hydraulic diffusivity is the ratio of hydraulic conductivity to the specific water capacity. All three terms can be written as functions of the volumetric moisture content. An equation for the simultaneous transfer of both liquid and vapor can be derived (Hillel, 1981).

# 3.9.2: Transport in Liquid Films

Haug (1980) has presented a conceptual illustration of mass transport and reaction in compost particle water films. This is shown in Figure 3.9. Consumption of oxygen by microbes causes a concentration gradient and oxygen diffuses from the free air space into the substrate-water-microbe matrix. Aerobic microbial metabolism consumes the substrate and oxygen. Microbial mass is synthesized and carbon dioxide, heat, water, and ammonia are produced. The metabolic end products are at elevated concentrations in the liquid phase and will diffuse toward the airspace.

Diffusion coefficients in a gas are about 10<sup>5</sup> times greater than in a liquid. Due to higher liquid vs. gas concentrations, however, the flux in a gas is not that much greater, being only about 100 times faster. (Geankopolis, 1983). The slowness of diffusion in liquids often limits the overall rate of processes that occur in liquids (Cussler, 1984). Some experimentally determined diffusion coefficients are presented in Table 3.9.

Cussler (1984) presents a number of methods for calculating diffusion in liquids and compares them for diffusion of oxygen in water at 25°C.

Diffusivities in liquids are often dependent on the concentration of the diffusing components. Oxygen diffusion in bacterial slime layers can be significantly lower than in water, sometimes as low as  $0.04 \times 10^5$  (Bailey and Ollis,



Figure 3.9: Conceptual illustration of mass transport of major components during composting (From Haug, 1980).

Solute	D (-10 <sup>-5</sup> cm <sup>2</sup> /sec)	
Carbon dioxide Oxygen Ammonia	1.92 2.10 1.64	

Table 3.9: Diffusion coefficients at infinite dilution in water at 25°C.

Source: Cussler, 1984.

### 1977).

Haug (1980) used a simplified model of gas transfer in a saturated matrix of solid substrate and microbes to estimate the effect of particle size on oxygen flux and the time required to satisfy the stoichiometric oxygen requirement. He concluded that diffusion can match the oxygen consumption rate if the particle size is sufficiently small. Particles thicker than 1.0 cm would have large diffusional resistances that could dominate the process kinetics. Particles of about 0.10 cm would be small enough for diffusion to meet demand. Oxygen diffusion would no longer exert control over the overall composting rate if particles are less than 0.05 cm in diameter.

### 3.10: Complete Heat and Mass Transfer Models

The method of volume averaging was used to derive the governing equations for heat and mass transport in a rigid medium by Ryan et al. (1981). Excellent agreement was found between theory and experimental work using a spatially perodic model of a porous medium for conductive and diffusive transport.

Latif and Lissik (1986) developed a non-distributed respiration model for heat and gases released during grain storage. The rate equation was a function of initial temperature and moisture content, and grain damage.

Chau et al. (1984) presented a numerical model for heat and mass transfer in spherical products. The effects of respiration, transpiration, conduction, convection and evaporative cooling were included.

Haug (1980) developed comprehensive simulations of continuous-feed completely mixed and batch models of the composting process. Finger (1975) developed a distributed heat and mass transfer model for windrow composting that was based on thermal heat conduction and the diffusion of oxygen into the compost pile.

#### CHAPTER 4

#### EXPERIMENTAL METHODS

# 4.1: Data Requirements

A windrow system without enhanced natural convection or forced aeration was selected for study. This system was selected because it closely resembled current dairy manure solids (DMS) handling practices: simply piling and turning the separated DMS before using it as a bedding material.

Based on a review of the literature, the data which must be used to validate a time-dependent spatiallydistributed finite-element model capable of predicting the time/temperature histories in a compost windrow include the following: temperature, gas concentrations  $(O_2 \&/or CO_2)$ , moisture content, volatile solids, bulk density, porosity, air-filled porosity, and windrow size change. The last four items were measured in core samples; the first two were measured using a probe, the design of which is described below. Table 4.1 gives a summary of the sampling methods and schedule for each variable.

## 4.2: General Experimental Design and Methods

The project was located at the dairy facility of the Kellogg Biological Station of Michigan State University. The facility, constructed in 1985, is a research and

Tab	ole	4.]	L:	Samp	ling	metl	hod	s and	l sci	hedu	lle	•
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Variable	Method	Samp 1 2	lin 3 4	g Da 5 (	ate 57
Temperature: Windrow:	* Campbell Scientific CR21X datalogger and AM32 multiplexer; 9 locations: Windrow 1-3 reps. averaged, Windrow 2-3 reps. recorded; 1 minute sampling interval,	xxxx	XXX	XXXX	<b>«</b> XX
Slab:	averaged each 15 minutes. * Same instrumentation; l location, 3 reps. averaged; same sampling interval.	XXXX	XXX	XXX	κxx
Air:	<pre>* Same instrumentation; l location; same sampling interval.</pre>	XXXX	XXX	XXXX	XX
Rel. Humidity:	* Same instrumentation; l location; same sampling interval.	XXXX	XXX	XXXX	xx
Gas Concentration:	* Probe sampling, evacuated cylinder storage, analysis for O2 and CO2 with gas chromatograph; 10 locations 3 replications.	x	x	x	x
Core Samples:	* Rotary corer; moisture content, volatile solids, coliform number, bulk density, porosity, free air space; 9 locations.	x	x		x
Windrow size & Shape:	* Windrow height, 30 to 36 locations; windrow height at probes, 12 locations; see text for method details.	<b>x</b> :	x	x	x

•

demonstration dairy farm that includes a 192 cow free stall dairy and milking parlor and a variety of support buildings. Four times each day, manure and spent bedding were flushed from free-stall alleys into a settling tank. The tank contents were agitated daily and the slurry was pumped over an inclined separator. The manure solids that came from the separator were then conveyed to a series of 4.5 m x 4.5 m bins inside a naturally ventilated building. The separated dairy manure solids (DMS) were allowed to accumulate for a week. Table 4.2 summarizes the physical characteristics of the dairy.

Table 4.2: Dairy characteristics.

Number of cows: Housed in free	192 Type: Holstein-Friesian stalls Four stall alleys Four feed alleys
Waste system:	Flushed 4 times per day with tip and gated tanks 5 % slope
	Well water and recycled lagoon water Stationary screen separator Conveyer
Bedding:	Dual lagoon 1/3 composted DMS1/2 skid steer bucket per week per stall
	2/3 chopped straw

When an experimental windrow was constructed, a batch of accumulated DMS was removed by a "skid steer" bucket loader, placed in a silage mixer, agitated, weighed and dumped on the ground. Samples for analysis of moisture content, volatile solids and coliform count were taken from the mixed windrow. The experimental windrow was constructed across a bin using a skid steer to place the DMS. Great care was taken to assure uniform placement. The skid steer operator was directed where to put each bucket load. Each bucket was placed so that the material fell from a uniform height of 46 cm (18 inches) above the windrow surface. The skid steer bucket was not used to shape the windrow: all final shaping was done manually with a shovel. All windrows had a trapezoidal prismatic shape.

The windrow was taken apart weekly, mixed in a silage mixer, weighed and formed into a new windrow using the methods described above. Exact uniformity of windrow size and shape was not possible between turnings because of losses due to composting and the difficulty of windrow construction. Each batch of solids was treated for 3 weeks. Two separate batches were monitored: one during the summer and the other during the fall of 1986.

#### 4.3: Probe Design and Placement

Methods of measuring temperature and gas concentration with probes in natural convection/diffusion based composting systems must meet several criteria. Accurate measurement must be possible. Probe placement and operation should disturb the windrow as little as possible. The probe should be sufficently rugged to withstand rough handling as well as the corrosive compost environment.

Accurate measurement of temperature levels and gas concentration are covered more extensively in the

appropriate sections. In general, temperature and gas samples must accurately reflect the actual temperature and gas concentration at the sampling location. The thermal conductivity of the probe, for instance, must be small enough that heat from neighboring high temperature zones is not conducted along the probe to lower temperature locations, leading to an inaccurate, high temperature measurement. Similarly, the gas sampling process should not draw gas from areas other than the intended sample area.

The method of probe placement can affect physical properties such as the bulk density and porosity in the area around the probe. This can in turn affect the heat and mass transfer which is being studied. If the probe is forced into the windrow, the surrounding DMS are compacted. If a hole for the probe is drilled into the windrow, the less dense material may settle away from the probe, exposing the probe to ambient conditions; this can be a serious problem with long term windrows (Mote, 1986). Placement of probes while the windrow is being made could lead to areas of the windrow "downstream" from the probe having different bulk densities than those on the "upstream" side.

The timing of probe placement must also be considered. Probes can either be inserted into the windrow whenever a measurement is made or they can be left in place for the duration of the study. Measurement on demand reduces both the number of probes that are needed, as well as their complexity. Large homogeneous windrows are required,

however, to permit probe insertion at a new location at each time without affecting the process. In-place probes allow many measurements to be made over time in the same location.

Operation of the measurement system should not affect the heat and mass transfer process in the windrow. This is particularly true for gas sampling. Suction of large volumes of gas draws outside air into the windrow. In forced aeration or suction composting systems this is not important. In natural convection or diffusion systems, however, this could greatly change the heat and mass transfer in the windrow, if only for a while.

There have been many attempts to develop probes for sampling temperatures and gas concentrations. Finstein (1980) placed a thermocouple in a slotted wooden dowel to reduce resistance to the probe placement. While studying forced aeration composting systems, Singley et al. (1982) used a probe that consisted of a perforated cylindrical diffusion chamber on the end of a pipe to measure both gas concentrations and temperatures at the same point in a windrow. A thermocouple was placed in the diffusion chamber. The probe was placed while the windrow was being built; air samples were removed as needed for analysis. Finger (1975) used a dissolved oxygen electrode mounted in a diffusion chamber at the end of a metal pipe. The probe was inserted into the compost windrow and the oxygen concentration measured at equilibrium.

Minimization of windrow disturbance is of prime

importance in this study; probes are therefore left in place. The probes are rigid, are inserted into the windrow after the windrow is formed and then left in the windrow, and permit both measurement of temperatures and sampling of gasses in the windrow.

The probe used in this study is shown in Figure 4.1. It allows gas collection and measurement of temperature at several points along its length. It consists of alternating sections of slotted wooden dowels with perforated copper tubing. The wooden sections reduce conduction along the probe and are not structurally affected by the temperature differences in the compost windrow environment, as is the case with materials such as plastic tubing. The perforated copper pipe acts as a diffusion and gas storage chamber. Dowel and copper pipe outside diameters are matched to reduce resistance to probe insertion and prevent oversized holes from being formed. The tip of the probe is turned to a point. Depending on the number of measurement locations on a probe, between one and four slots are cut in each dowel section. Thermocouple leads and a polyethylene tube are laid in each of the slots; this pair continues down the probe until it reached the location to be measured. The tubing terminates inside the diffusion chamber while the thermocouple is extended out one of the holes in the copper tubing so that it senses the compost temperature outside the probe.

Probes were constructed and placed so that 10 locations



Figure 4.1: Probe for sampling temperatures and gas showing alternating wooden and copper sections. Probes had one to four perforated copper diffusion chambers depending on location. ı
in a cross-section of the compost windrow could be monitored. Triplicate sets of probes were constructed to allow for three cross-sections (0.4 meters apart) to be studied for a total of 30 points or 10 locations with 3 repetitions. Figure 4.2 is a cross sectional view of the windrow showing typical probe placement. Location 7 was not



Figure 4.2: Typical temperature and gas sampling locations.

monitored because the windrows were not large enough. Figure 4.3 shows an orthogonal projection of the windrow and a collection system.

## 4.4: Temperature Measurement

#### 4.4.1: Equipment and Method

Copper constantan thermocouples were connected to a Campbell Scientific CR21X datalogger through a 32 channel multiplexer. The datalogger provides reference temperatures and the calibration curves for voltage-to-temperature conversion. A different method of connecting the



- A. Bulk material sampling locationB. Relative humidity sensor
- C. Gas sampling/
  - thermocouple line
- Datalogger D.
- Multiplexer Ε.
- F. Gas sampling ports
- Figure 4.3: Orthogonal projection of test windrow showing temperature and oxygen probe placement. Windrow height and base dimensions are typical.

thermocouples to the datalogger was used in each of the two experimental windrows. In Windrow 1, the thermocouples from the corresponding locations on different probes were connected in parallel and then run to the datalogger. This allowed an average temperature for each of the 10 locations to be obtained while using up fewer input ports on the datalogger. In Windrow 2, the thermocouples from each probe location were run directly to the datalogger so that the temperatures at all 30 locations were separately monitored. Temperature in the concrete slab under the compost, ambient temperature and ambient relative humidity were also monitored. The temperatures and relative humidities were sampled every minute and averaged every 15 minutes.

## 4.4.2: Error Analysis and Calibration

Table 4.3 summarizes the sources of possible error with the Campbell CR21X datalogger and AM32 multiplexer used with copper-constantan thermocouples. According to the Campbell literature (Campbell Scientific, 1985) the maximum error is ±1.5°C. A more detailed explanation of these calculations is included in Appendix A.

The largest source of error shown in Table 4.3 is due to the difference in thermocouple output. Accordingly, the thermocouples were subjected to two tests. In the first the complete measurement system was tested by inserting thermocouples into an ice bath and then heating the water until it boiled. Temperatures were recorded every 5 seconds and averaged every minute using the same datalogger used in

Table 4.3: Temperature measurement err	ors.	•
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ERROR SOURCE	TEMPERATURE (C)			
Reference junction temperature Thermocouple output Thermocouple voltage measurement Reference linearization Output linearization	$\begin{array}{r} \pm & 0.5 \\ \pm & 1.0 \\ \pm & 0.05 \\ \pm & 0.001 \\ \pm & 0.001 \end{array}$			
Total error	± 1.5			

the field. At the icepoint the thermocouples had an average temperature of 0.42°C with a standard deviation of 0.13°C. At boiling, the average and standard deviation were 99.0°C and 0.2°C, respectively.

The second test involved inserting the 33 thermocouples that were actually used in the experiment into a constant temperature water bath. Temperatures were recorded every 5 seconds and averaged over a minute. The water was agitated with a propeller attached to a 3/4 hp drill. The water temperature was varied between 27°C and 69°C, with four different temperature plateaus being held. The results of this test are shown in Table 4.4, with the average and standard deviation of all thermocouples at a certain time being given. This method was chosen because it was hard to maintain the water bath temperature exactly constant over time. Sample data from this experiment are given in Appendix B.

As can be seen from the data in Table 4.4, the

Number of Data Points	Average Temperature (°C)	Average Standard Deviation
30	27.556	0.004
30	35.554	0.271
25	42.118	0.001
25	55.742	0.008
36	68,119	0.054

Table 4.4: Water bath calibration of 32 thermocouples.

variability between thermocouples was very low. Only the second temperature step showed an average standard deviation greater than 0.1°C. This is probably because heat was first applied in this step and the induced convection currents had not stabilized at the time of monitoring.

## 4.5: Gas Sampling and Analysis

## 4.5.1: Equipment and Method

Thin walled plastic tubing was run from each probe diffusion chamber in slots cut in the wooden dowel to the top of the probe (Figure 4.1). A connection was made to a flexible plastic tubing. The total length of tubing to each location was 4.9 m. The other end of the tube was connected to a 3-way valve (Figure 4.4). A 3 cc syringe body plugged with a rubber septum was attached to one of the two remaining valve outlets. The third was open to the atmosphere. All joints were sealed with silicon caulk and were inspected before a sample was drawn. Joint integrity was tested weekly when the windrow was turned and the probes were removed. Other pieces of the apparatus consisted of a



Figure 4.4: Gas sampling apparatus. Valve is in position to allow sample to be drawn from diffusion chamber in pile.

50 cc rubber pipette bulb, a 6 cc syringe and needle, and evacuated test tubes with rubber septums. Samples taken from Windrow 2 had a plastic collar around the probe to discourage gas flow along the probe during sampling.

Gas samples were drawn at four times during each week of treatment: on the 1st, 3rd, 5th and 7th days from the start of each turned windrow. Samples from locations closer to the surface were taken first. The same order of sampling was maintained throughout the experiment. A total of thirty windrow and 3 ambient samples were drawn each day.

When gas samples were taken, the long sampling tube was evacuated by attaching the compressed pipette bulb to the open end of the 3-way valve, opening the valve, and allowing the bulb to expand to its normal shape. This removed the gas present in the tube since the previous sample. Gas from the diffusion chamber was sucked up to the valve. This gas had previously reached equilibrium concentration with the gas outside the diffusion chamber. The valve was then turned to open the passage between the diffusion chamber and the 3 cc syringe body. A 6 cc sample was drawn from this and discarded. Six cc was again withdrawn, approximately 0.2 cc was ejected to clear the needle, and the sample was immediately injected into the evacuated test tube. The volume of the test tube was 4 cc; gas samples were stored at about 1.5 atmospheres. Two cc of gas at pressures greater than one atmospheres was available for gas analysis. The evacuated test tubes are commercially available and have

been successfully used to store samples for 2 weeks (Grofman, 1986). Storage tube septums were sealed with silicon caulk after the sample was injected into the test tube to protect the sample for longer periods of time.

Gas samples were analyzed for carbon dioxide and oxygen on a Carle Model 8700 Basic Gas Chromatograph. A silica-gel column was used to analyze the carbon dioxide. A 5A molecular sieve with a 60/80 mesh column in series with the gel column separated and analysed oxygen and nitrogen. Twoto-four standard gases were used for developing calibration curves over a range of 1 to 20 percent for both carbon dioxide and oxygen. Concentrations were calculated based on peak heights. A Hewlett-Packard model 3390-A reporting integrator recorded areas under the peaks as back-up data.

#### 4.5.2: Error Analysis

There are several potential sources of error in the gas sampling and analysis system. The sources of error are shown in Table 4.5.

Table 4.5: Potential sources of error in gas sampling, storage, and analysis.

1.	Gas drawn into sample from outside sample area.
2.	Leaks into gas sampling tubes before sampling.
3.	Diffusion through needle into sample before
	injection into the sample tube and/or G.C.
4.	Flow of sample out of sample storage tube and
	diffusion of gases (primarily oxygen) into sample
	storage tube.
5.	Withdrawal of sample at less than atmospheric
	pressure.
6.	Gas chromatograph calibration.
-	

7. Gas chromatograph problems.

# <u>4.5.2.1:</u> Effect of Air Being Drawn into Sample from Outside Sampling Area

The error caused by gas being drawn into the sample from outside the sample area is indeterminate. A decrease in pressure at the inlet to the sampling tube caused by suction applied at the sampling end causes gas to move into the tube. Gas will be drawn from those volumes with the least resistance to flow. In an ideal situation, this gas comes from a spherical volume immediately surrounding the inlet. Changes in the cross-section of the probe will cause the hole cross-section around the sampling point to be larger than the probe itself (Figure 4.5). The air in this void space has less resistance to flow than air in the dense layer around the probe.

Three factors could increase this potential error. First, if a portion of the probe has a blunt tip or a crosssection that is much larger than average, the hole in the windrow is larger than the probe. Second, even if the probe and hole is initially the same diameter, over time the hole near the surface can become larger due to windrow settlement. As mentioned earlier, this problem was encountered with the use of permanent probes left in the windrows for one month or longer (Mote, 1986). Both of these factors increase the likelihood that ambient air could be sucked into the sample. Finally, the use of a vacuum pump to draw samples exacerbates this problem.

In order to estimate and control this source of error, three approaches were used: calculations of potential



Figure 4.5: Cross-section of probe insertion hole showing annular void space created by probe insertion.

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error, probe design, and experimentation. Calculation of potential errors are made for two cases: (1) an air-filled void around the probe, and (2), no void. Case 1 assumes that air only comes from the annular void around the probe. The affected height is calculated with the equation

$$l_{a} = \pi (r_{o}^{2} - r_{i}^{2}) / V_{s}$$
 (4.1)

where	$^{l}a$	=	length of air annulus affected by sample
			withdrawal
	ro	=	outer radius of annulus
	$\mathbf{r}_{i}$	=	inner radius of annulus
	V,	=	volume of the sample

In Case 2, the air is assumed to come from a spherical volume around the sampling point. The affected radius is calculated with the equation

$$r_a = (V_s / \pi FAS)^{1/3}$$
 (4.2)

where  $r_a$  = radius of compost air affected FAS = free air space

A range of annular ring cross-sections for Case 1 and free air space for Case 2 are assumed. Sample size varies for both cases. The estimated volume of the sampling apparatus is also considered.

In the first Case 2 analysis, a range of large sample volumes from 100 to 1000 cc was looked at. Assuming that 6 inches is the largest acceptable radius where no sample contamination occurs, 300 cc samples are the largest that can be safely taken for all potential compost free air space. This leads to the rejection of two methods of gas analysis: a Bacharach Fyrite tester and a flow-through gas chromatograph. Analysis of Case 1 indicated that larger sample sizes and small void space led to samples being drawn from further away. Large sample size and large annular void spaces draw air from less distance. It is easier for outside air to get into the windrow and affect the long term composting process in this case, however. A Case 2 analysis with smaller sample volumes indicate that for most tube diameters and lengths, the radius of influence is less than 6 inches.

The air sampling system incorporates two features to reduce the possibility of contaminated air being sucked into the system. Probes are designed and constructed with a constant cross-section as determined by the materials and the need for probe rigidity. Diffusion chambers are incorporated into the probe to provide a reservoir of gas equilibrated to compost gas concentrations. The volume of the sampling system is shown in Table 4.6.

# 4.5.2.2: Effect of Withdrawing Succesive Samples on Changes in Gas Concentration

An experiment was conducted to measure the changes in gas concentration as successive samples were withdrawn from a sample location. The probes were inserted into the windrow in the same manner and locations as for an actual experiment. Successive 5 cc samples were withdrawn until 75 cc was removed. Four different windrow locations were sampled to provide a range of windrow conditions: 1, 5, 8, and 10 (Figure 4.6). The results of one of the sampling runs from Location 1 are shown in Figure 4.7. The

Vo	lume (cm <sup>3</sup> )
Sampling system:	13.5
Tube	5.0
Syringe	<u>7.2</u>
Diffusion chamber	25.7
Sample Size	50.0
Rubber Bulb	6.0
Discard	<u>6.0</u>
Sample	62.0

Table 4.6: Internal volume of sampling tubes and diffusion chamber.



Figure 4.6: Sampling points for sequential gas sampling.



Figure 4.7: Sequential sample gas concentration, Location 1.

concentration of carbon dioxide in the first 5 cc sample is low but rises close to its final value by the third sample. Oxygen concentrations follow the reverse pattern. The lower values of the 5 cc sample indicate that there might be some leakage into the system, but that this is flushed out by the adopted experimental method. The constant value at the 65 cc volume, which corresponds to the usual sampling point, indicates that no contamination of the air sample occurred from this source. Results of the other tests are shown in Appendix C.

## 4.5.2.3: Effect of Leaks into Gas Sampling System

Leakage into the gas sampling lines was discouraged by sealing all joints with silicon caulk. Each day before

samples were taken, the integrity of the lines and silicon seals were checked and repaired if necessary. At the end of each weekly batch, the probes were removed from the windrow and each line was leak tested in a water bath. Blocked or leaky lines were replaced.

# 4.5.2.4: Effect of Diffusion and/or Gas Flow into Syringe and Gas Storage Containers

Solutions to the third potential error were incorporated into the sampling procedures. To discourage diffusion into or out of the syringe, the syringe was kept in the sampling apparatus for 6 to 10 seconds after the second 6 cc sample was drawn. This allowed pressures inside the sampling apparatus to approach atmospheric. After the removal of the syringe from the apparatus, the ejection of approximately 0.2 cc cleared the needle of any ambient air that might have entered.

At the start of the experiment, the use of the evacuated test tubes for gas storage was assumed to be accurate based on the experience other researchers at MSU (Groffman, 1986): analysis within 2 weeks of sampling does not affect accuracy. Samples from the first windrow were analyzed according to that timetable. Due to problems with the gas chromatograph, however, analysis of the second set of gas samples was delayed beyond the two week limit. In addition, the oxygen levels in the center of the windrow seem high. An error was suspected in the gas concentration analysis procedure. Accordingly, two experiments were conducted to assess the integrity and durability of the

storage system.

A possible source of error is the withdrawal of air samples at less-than-atmospheric pressure. This occurs if sample withdrawal caused sub-atmospheric pressures in the syringe and sample storage tube. To test this, ten evacuated tubes were filled with nitrogen. Successive 1 cc samples were withdrawn and analyzed on a gas chromatograph. Figure 4.8 shows the effect of the sample volume withdrawn on the measured oxygen concentration.

Syringe internal pressure was estimated based on the volume of the sample container, the volume and number of withdrawals and the initial pressure. Comparison (Figure 4.9) of the calculated syringe internal pressure to measured oxygen concentrations indicates two almost linear segments. Assuming that the initial and atmospheric oxygen concentrations are 0 and 20.95 percent, respectively, the influx as a function of sample number, sample volume, and calculated internal pressure was calculated. The relationship between influx and calculated internal pressure is shown in Figure 4.10.

The preceding results needed to be converted from the 3 cc sample container size used in the calibration experiment to the 4 cc size used in windrow monitoring. To accomplish this, the influx values for the 3 cc container were converted to volume influxes and then percent influx for the 4 cc container was calculated. The calculated 3 cc container internal pressures that correspond to the volume



Figure 4.8: Effect of cummulative gas withdrawal on oxygen concentration.



Figure 4.9: Effect of sample pressure (calculated) on oxygen concentration.



Figure 4.10: Percent influx as a function of internal pressure.

withdrawn were used with the 4 cc influx values in a linear regression. This equation was used to calculate the influx at internal pressures corresponding to those occurring after each successive 0.55 cc sample volume was withdrawn from the 4 cc container. Finally, a linear regression equation was run on sample withdrawal number vs influx data to arrive at an equation useful for transforming the experimental gas concentration data. The resulting equation is

 $In_4 = 0.0198 * S + 0.002$  (r = 1.000) (4.3) where  $In_4 = 4$  cc influx, decimal

S = Sample number

Observations of sample containers that had their rubber septums covered with silicon caulk after the samples were injected indicated that there was some leakage out of the

sample tube. Since calculations of internal pressure indicated that changes in starting pressure influenced the speed at which a vacuum was produced in the sample container, it was necessary to get an estimate of the error due to variations in sample starting pressure. I assumed that the worst case would occur if enough gas had leaked out of the sample container so that the gas was at atmospheric pressure. In this case, all syringe sample withdrawals would be at less than atmospheric pressure and so subject to an influx of air due to the pressure differential. I assumed that this influx corresponded to the second and steeper slope in the data shown previously in Figure 4.10.

In order to quantify this relationship a series of calculations similar to the previous case was performed. All calculations are shown in Appendix D. The resulting regression equation (r = 0.998) for sample number vs. influx is given by:

 $In_4 = 0.0851 * S + 0.0027$  (4.4)

The effect of the withdrawal of a sample of a given volume and measured gas concentration on actual gas concentration is described by Equations 4.5 for oxygen and Equation 4.6 for carbon dioxide. For a given sample volume the effect is linear and can be described as follows for each gas:

O2:  $O_a = (O_m - In * O_e) / F$  (4.5) CO2:  $C_a = C_m / F$  (4.6)

where	0	=	oxygen concentration, percent
	С	=	carbon dioxide concentration, percent
	а	=	actual
	m	=	measured
	е	=	ambient
	In	=	influx gas in syringe, decimal
	F	=	original gas in syringe, decimal
		=	1 - In

Equations 4.3 or 4.4 can be substituted into Equations 4.5 and 4.6 to achieve the desired correction.

Four different correction calculations were considered. The first, the low influx method, involves the insertion of Equation 4.3 into Equations 4.5 and 4.6. The second method was accomplished by inserting the high influx equation 4.4 into Equations 4.5 and 4.6. The third method was achieved by calculating the average of Methods 1 and 2. The fourth method was based on two assumptions: the measured carbon dioxide was correct and the sum of carbon dioxide and oxygen concentrations was approximately 21 percent. With this method, measured carbon dioxide was subtracted from 21 % to achieve the oxygen concentration.

Method 3, based on average values, was chosen as the most appropriate correction calculation. Method 4 does not make the desired corrections. Methods 1 and 2 are subject to the uncertainty of the initial sample pressure at the start of analysis. The average method is at best a compromise, because it is subject to the same uncertainty.

The measurement error due to the correction factor is ±1.0 % oxygen at low concentrations and ±0.25 % at high concentrations. Measurement errors for carbon dioxide are ±0.25 % at low concentrations and ±1.0 % carbon dioxide at

high concentrations.

The effects of storage system type and time were also examined. Leakage of gas through the hole in the septum due to initial overpressure followed by diffusion of oxygen into the sample storage tube could occur and affect measured results.

Evacuated test tubes were filled with pure nitrogen to 1.5 atmospheres pressure. Half of these had uncovered rubber septum tops as in Windrow 1 samples. The rubber septum tops of the other half were covered with silicon caulk to block the injection point, similar to Windrow 2 samples. Five tubes from each treatment were analyzed each week for 5 weeks. The same four point calibration curve was used to calculate the percent oxygen.

There were no observable oxygen peaks in weeks 1 to 3. Week 4 samples showed small oxygen concentrations that were statistically the same at the  $\alpha = 0.05$  level. Both covered and uncovered samples were significantly lower than the initial oxygen concentrations. Week 5 covered samples were again significantly lower than week 4 covered samples. The covered samples from week 5 showed a very large variance and the average was significantly higher than any other time and treatment. Two of the four samples from this group exhibited the same concentration as the covered samples but the other two were quite higher. The covered samples exhibited small bubbles in the silicon, indicating that some gas probably escaped from the uncovered tubes. This is also

supported by the larger variability in week 5 uncovered samples. The results of this experiment do not elucidate the effect of storage time and treatment although they seem to indicate that for the covered system there is no loss of gas and for the uncovered system that it was only after 5 weeks of storage that a loss of gas in some storage containers may have occurred.

Tentatively, it can be concluded that storage time has no effect on the covered samples used in Windrow 2. While the uncovered samples do show greater variability in week 5, this was far beyond the actual storage time for Windrow 1 samples, and the time effect could be ignored.

## 4.5.2.5: Gas Chromatograph Calibration and Errors

Some potential for error is present in the procedures used to calibrate the gas chromatograph. Initially, I thought that point calibration would be adequate based on the experience of other researchers using the same gas chromatograph (Dilley, 1986). It shortly became apparent that more points were needed and another bottled standard was used for two point calibration; most of the samples from Windrow 1 were measured using two-point calibration. Samples from Windrow 2 were analyzed using a four point calibration curve. The additional standards were made up volumetrically.

The bottled standards were manufactured with a fixed, absolute error. The volumetric standards were mixed before each sample analysis session. The method of mixing involved inserting septums into 160 cc sample bottles, alternately evacuating the bottles with a vacuum pump and filling them with nitrogen gas, and then filling the evacuated bottle with precalculated amounts of oxygen, carbon dioxide, and nitrogen to 2 atmospheres pressure. 30 and 60 cc syringes were used to fill the bottles. Table 4.7 summarizes the standards and variability used in this study. Error calculations for the volumetric standards are given in Appendix E.

		Gas Conce	ntration	
Standard	Lev tev) Lev	rel mos.)	Std. 1 (% Ati	Dev. mos.)
	co <sub>2</sub>	0 <sub>2</sub>	co2	02
1	5.079	20.524	±0.10	±0.61
2	0.983	4.97	±0.002	±0.15
3	10.0	10.0	±0.226	±0.226
4	1.0	20.0	±0.238	±0.167

Table 4.7: Gas concentration standards used in gas chromatograph calibration.

The gas chromatograph itself presented a significant source of error at times. Two types of problems arose. When a sample had a significantly lower concentration than the preceding sample, there was a lag in the apparent concentration. This caused the first new subsample to appear to have a higher concentration than it actually did.

The second problem was due to the erratic behavior of the gas chromatograph when analysis of Windrow 2 samples were to begin. As the first day's samples were analyzed, the gas chromatograph became more erratic. Finally, not even standards would behave consistently. The problem was tracked down to a faulty injection valve. The gas chromatograph behaved correctly after replacement. Concentration data from two days were lost, however.

4.6: Core Sampling Method

# 4.6.1: Review of Sampling Methods and Corer Design

Moisture content, volatile solids, coliform numbers, bulk density, porosity and free air space are expected to vary spatially. Accurate samples must be taken to understand the heat and mass transfer process in DMS composting and to provide data for future modeling efforts. Sample location in the windrow must also be known accurately. The sampling process, however, must disturb the windrow as little as possible. Sample handling and storage are also important but will be covered in later sections.

Moisture content and volatile solids samples are the least difficult to obtain. Sampling does not change either of these two variables, but it may disturb the windrow. Hoyle and Matingly (1954) used a hollow auger that was 61 cm long and 2.67 cm in diameter to take vertical samples from 61 x 61 x 61 cm composting bins. The material was analyzed for moisture content, ash and various forms of nitrogen. A grid was used to ensure that samples were not taken from the same location in the windrow. No mention was made of the effect of sampling on the composting process. Finstein et al. (1980) used a clamshell posthole digger (5 inch diameter) to obtain samples from 7 ton windrows. Great care must be taken with sampling for micro-organisms to prevent contamination. Sampling for bulk density, porosity, and free air space is more difficult. Bulk density determinations are based on both sample weight and initial volume; the act of sampling can change the volume of the sample.

Disturbed samples can be used to get an estimate of bulk density. Several methods that use disturbed samples and the addition of water in calibrated containers have been developed (Singley et al., 1982). These methods do not adequately account for the effect of the overburden of the compost and the compaction that it causes. The value of the bulk density at a particular location over time is hard to obtain as well. Several methods of determining soil bulk density are described in the soil mechanics literature (ASTM, 1986). These methods were either quite destructive of the windrow or the required equipment was not available for use in this study.

Core samplers are frequently used for soil bulk density determinations. Raper and Erbach (1985) note that samplers can either be hammered, driven in at a constant speed, augered or inserted into the soil by some combination of the above methods. Evidence that the length of the core sample is shorter than the sampling depth indicates that compaction may be a problem (Wells, 1959). In order to minimize the

effects of compaction, Baver (1956) recommends using at least a 7.62 cm diameter tube.

Core sampling device design greatly affects sampling accuracy (Raper and Erbach, 1985). Compaction can be avoided by sampler point and interior sampler design. Shaping and sharpening the sampler point shears the soil instead of deforming it ahead of the sampler and also directs unwanted soil to the outside of the sampler. Providing a taper or interior sampler volume greater than the interior diameter of the cutting head allows the sampled material to expand and reduces the friction resisting the penetration of the probe. Coating the interior with teflon does not appear to make a significant difference in the sampled core bulk density (Raper and Erbach, 1985).

The accuracy of standard soil corers was analyzed by Baranowski (1983) with forest soils. He found that the core method could reveal intertreatment densities to accuracies no greater than  $\pm 50 \text{ kg/m}^3$ , even with favorable conditions, careful sampling and adequate replications. Under less favorable conditions, the error was as much as 5 times larger.

Peat sampling provides a system analogous to compost sampling; both involve taking samples of a fibrous organic material. Peat sampling equipment includes the use of Macaulay samplers, core cutters and stationary piston samplers (Jarret, 1986). Bulk density from these samplers can be determined by the kerosene, paraffin, or cylinder

methods (Nat. Res. Counc. Can., 1979). The most interesting method required a cylindrical cutter attached to a core holder and base, powered by a hand drill. In this method, bulk density was determined by dividing the oven-dry weight of the peat core by the inner volume of the cylinder. Stanek (1980) compared the results of bulk density determinations made by the paraffin and cylinder method to the kerosene method which was considered to be the most accurate. He found that the cylinder method correlated well with the kerosene method (r = 0.979). Based on this information a method was adapted for sampling a compost windrow.

## 4.6.2: Comparison of Core Sampling Methods

The rotary corer required some skill to operate properly. Unless the core was held very steady, it would rotate off-course and take in material from a volume greater than the volume intended. When the corer was removed, some material from around the lip occasionally fell into the hole. The sides of the cylindrical hole did not appear to be excessively disturbed. A narrowing of the hole began within 2 minutes and the bottom appeared to rebound following removal of overburden pressure. The end of the core sample showed evidence of the rotation and usually broke off cleanly. The length of the core sample was usually 10 to 20 % less than the hole in the windrow, indicating that some compaction had occurred in the corer, windrow or both. When the corer was used to take samples of

low density material such as that near the windrow "toe," it was observed to push some material aside. This was not observed in the more dense portions of the windrow. Two different length and diameter corers were tested. The smaller diameter corer was harder to insert into dense portions of the windrows; it was unable to penetrate windrows composed of long straw.

An experiment was conducted to estimate the accuracy of several core sampling methods for bulk density, porosity and free air space determinations. Three 55 gallon drums were filled with 1 week old separated manure solids that had been mixed in a silage mixer. After leveling the tops, three sampling methods were used: (1) a 20.32 cm diameter ring, (2) a short 7.78 cm diameter rotary corer and (3) a long 5.08 cm diameter rotary corer. The rotary corers were powered by a 3/4 hp electric drill.

Three samples of approximately 30 cm were taken from each barrel by the two rotary corers. The ring sampler was then pushed and rotated into the surface and the sample was then removed by hand. Approximately 30 cm of material was removed from the barrel and the ring sampling procedure was repeated. This was repeated to obtain the third ring sample. The above steps were repeated in each of the barrels until 3 replications of sample depth for each method had been obtained. Samples were stored and analyzed for weight, moisture content and volatile solids. Bulk density, porosity and free air space were calculated. The methods of

analysis and calculation are described below in the appropriate sections. Detailed results are given in Appendix F.

Wet bulk densities ranged from 198 to 566 kg/m<sup>3</sup> depending on the sampling method and depth. Precision was good with the average coefficient of variation for each method at all depths being 8.7, 10.9 and 10.0 % for the ring, short corer, and long corer methods, respectively. Using the two-tailed Student's t test, the three methods were significantly different in at least two of the three depths at the 90 % level. The short sampler always gave the largest bulk densities followed by the long sampler and the ring method.

Free air space values in this experiment ranged from 0.850 to 0.471. Using the same statistical test, the three methods were significantly different in at least two of the three depths at the 90 % level. The average coefficient of variation for each method at all depths was 3.2, 7.5 and 3.0 % for the ring, short corer and long corer methods, respectively.

The ring method was not chosen for use because it could not be used to sample windrow interior bulk densities. The long corer with the small diameter was not chosen because of the difficulty encountered with inserting it into some windrows made of long straw. The short wide sampler was selected because it would be able to penetrate a wider range of compost material and its greater diameter would be less

succeptible to errors in the radius determination than the longer, narrower sampler.

# 4.6.3: Description of Experimental Core Sampling Method

Samples for determining moisture content, volatile solids, bulk density and free air space were obtained on the 1st, 3rd, and 7th days after a windrow was turned. A 7.78 cm diameter rotary corer attached to a 3/4 hp electric drill was used to drill vertical sections out of the windrow. The corer is shown in Figure 4.11. The cutting edge is serrated to cut through fibrous material and slanted away from the path of the core opening to push away any material not directly in the path of the core opening. To relieve friction from the surrounding windrow, the cutting head exterior dimension is greater than the core body. Similarly, the interior diameter of the cutting head is smaller than that of the corer body interior to allow the compost material to expand and give reduced resistance to the entry of material at the cutting head opening.

The corer allowed vertical cylindrical compost samples of variable length to be removed from the windrow. The vertical center of each approximately 30 cm core sample was at the same horizontal and vertical point as a temperature and gas measurement location (Figure 4.12). At least 9 samples were taken at each time. No replicates of these samples were taken because additional samples would have seriously disturbed the windrow.

The sampling procedure involved first determining the



Figure 4.11: Rotary core sampler.

Center of sampling location

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Figure 4.12: Core sample locations. Cylindrical in shape, the center of the sample was located at approximately the same point in the yz plane as the temperature/gas sampling point.

location of each sampling point below the windrow surface. The beginning and ending locations of each sample were calculated. A catwalk placed directly above the sample location provided a place for the operator to stand while taking core samples. A colored scale on the side of the corer guided the operator to the proper sampling depth. The exact hole depth was measured immediately afterwards. The compost sample was removed from the corer and placed into either a ziplock bag for moisture content and volatile solids analysis or a "whirlpak" for coliform analysis. If a visible color difference was present in a sample, the sample was split and separate analyses performed. The holes created by the withdrawal of samples were filled with DMS compost material of a similar age, lightly compacted and marked.

In the experimental method adopted, a single large sample from each location was taken at each time. The first

set of samples was taken from one side of the windrow after the windrow was one day old. The second set was taken from the opposite side on the third day and the third set was taken on the seventh day from the same side as the first set, approximately 1.5 feet away. This method diminished the effect of sampling on the transport processes, but the method could be criticized because the second samples were taken from an area that was different.

## 4.7: Moisture Content and Volatile Solids

#### 4.7.1: Methods and Calculations

Gravimetric moisture content (wet basis) and volatile solids (total solids basis) were determined using <u>Standard</u> <u>Methods for the Examination of Water and Wastewater</u> (AWWA, 1976). Gravimetric moisture content on a dry basis, volumetric moisture content and volatile solids on an ash basis were calculated.

Samples were removed from the pile as described in the bulk sampler section, and were placed in ziplock bags and stored at 2°C. Samples were first mixed by hand kneading the bag with the sample still inside. Sub-samples were removed by tongs and placed in ceramic crucibles. The crucibles had previously been fired in a furnace at  $550^{\circ}$ C ±  $50^{\circ}$ C for 1 hour, cooled in a dessicator and weighed. The wet samples and crucible were weighed and dried in an oven at  $103^{\circ}$ C ±  $2^{\circ}$ C. After 24 hours, the sample were removed, cooled in a dessicator and reweighed.

Volatile solids were determined by ashing the dry

matter in covered crucibles at 550°C ± 50°C for 1 hour. If black or red material remained in the crucible at this point, the crucibles were placed back in the furnace for 5 minutes, sans covers, to completely ash the samples. After removal and cooling in a dessicator, the crucible and ash were weighed.

A Precision Scientific model 1254 oven, a model FD204C Hoskins Electric furnace, and a Sartorius model 1265 MT scale were used in this procedure. The scale is accurate to ± 0.001 g.

The following calculation for gravimetric moisture content (wet basis) was used:

 $MC_{wb} = [1 - (M_{CS} - M_C)/(M_{CSW} - M_C)] \quad (4.7)$ where  $MC_{wb} =$  moisture content, wet basis, decimal  $M_X =$  Mass of x, g csw = crucible, solids and water cs = crucible and solids c = crucible

One of the problems with wet basis moisture content calculations is that changes in the mass of water change both the numerator and denominator. This makes it impossible to directly compare the moisture contents at any two points in the process.

If moisture contents are expressed on a dry basis, however, only the numerator changes. The dry basis calculation is as follows:

$$MC_{d} = M_{w} / M_{d}$$
(4.8)

d = dry solids

A comparison of wet (% wb) and dry basis (% db) moisture contents is presented in Table 4.8. Dry basis moisture contents are much more sensitive to changes in the weight of

Table 4.8: Comparison of moisture contents expressed on a wet and dry solids basis.

Method Moisture Content (%)									
MC <sub>w</sub>	90	80	70	60	50	40	30	23	20
MCd	900	400	233	150	100	67	43	30	25

water that is present in a substance.

Volatile solids were calculated with:

 $VS = 100 * [1 - (M_{ca} - M_{c})/(M_{cs} - M_{c})]$  (4.9) where VS = volatile solids, dry solids basis, decimal

where VS = volatile solids, dry solids basis, decimal ca = crucible and ash

Expression of volatile solids on a total solids basis suffers the same drawback as the wet basis moisture content measurement. Both the numerator and denominator change as the reaction progresses. This makes it impossible to directly compare the volatile solids at any two points in the process.

Another way of looking at substrate consumption using the same data is to calculate the change in the volatilized solids based on the ash fraction that remains.

VS<sub>a</sub> = M<sub>v</sub> / M<sub>a</sub> (4.10)
where VS<sub>a</sub> = Volatile solids ash fraction, decimal
v = volatilized solids
a = ash solids

Since the ash fraction should not change unless additional inert material is added to the composting process, VS<sub>a</sub> should provide a stable base for evaluating substrate consumption.

Table 4.9 illustrates the difference between the two methods of expressing substrate consumption. Ash solids expressions of substrate consumption indicate a much larger decrease in substrate than the volatile solids method.

Table 4.9: Comparison of volatile solids expressed on a dry and ash solids basis.

Method Substrate					(%)			
vs	95	93	90	89	85	82	80	
vs <sub>a</sub>	1900	1329	900	809	567	456	400	

Three replications of each measurement were done initially in Windrow 1. Five were used initially in Windrow 2. Outlying data were rejected with the Q test (Davis, 1981). If the variance was greater than one percent, an additional 5 samples were run.

## 4.7.2: Sensitivity Analysis

The sensitivity of moisture content and volatile solids determinations to errors in their measurement was determined using the theory of the propagation of errors (Parratt, 1961; Topping, 1951). The following paragraphs summarize the derivation presented in Appendix G, which was orginally given by Parratt (1961).
A result U, which is computed from the quantities X and Y has the following variance for indeterminant errors:

$$s_r^2 = (\partial U/\partial x)^2 s_x^2 + (\partial U/\partial y)^2 s_y^2$$
 (4.11)  
where  $s_x^2$  and  $s_y^2 = variances associated withmeasurement of X and Y.$ 

For addition or subtraction the variance of the calculated result is given by the sum of the variances:

$$s_u^2 = s_x^2 + s_y^2$$
 (4.12)

If U is a result of multiplication or division such as

$$U = x^{a} y^{a} \qquad (4.13)$$

then the variance is given by

$$s_u^2 = [(ax^{a-1}y^b)^2 s_x^2 + (bx^ay^{b-1})^2 s_y^2]$$
 (4.14)  
The fractional variance is given as:

$$s_u^2 / u^2 = [(s_x/x)^2 + (s_y/y)^2]$$
 (4.15)

The fractional variance can be put in terms of percentage by multiplying by 100.

Fractional variance for the wet basis moisture content calculation is given by:

$$s_{MCwb}^2 / MC_{wb}^2 = [((s_{CS}^2 + s_{C}^2) / M_d^2) + ((s_{CSw}^2 + s_{C}^2) / M_{wS}^2)] * 100$$
 (4.16)  
where ws = wet solid

A similar sensitivity analysis can be run for the dry basis moisture content calculation. The equation is

 $s_{MCdb}^{2} = (1 / M_{d})^{2} s_{ws}^{2} + (M_{ws} / M_{d}^{2})^{2} s_{d}^{2} (4.17)$ Where  $s_{ws}^{2}$  = variance of wet solids measurement  $s_{s}^{2}$  = variance of dry solids measurement = ±0.002 g The variance of volatile solids (dry solids basis ) is given by

$$s_{VS}^2 / VS^2 = [((s_{Ca}^2 + s_{C}^2) / M_a^2 + (s_{CS}^2 + s_{C}^2) / M_d^2] * 100$$
 (4.18)  
where  $s_x^2 = variance$  associated with measurement

Despite the large observed  $VS_a$  changes,  $VS_a$  is still subject to the same errors present in the volatile solids determination. Errors in  $VS_a$  determination were analyzed for selected data using a sensitivity analysis procedure similar to that used for VS. The equation developed was:

 $s_{VSa}^2 = (1 / M_a)^2 s_d^2 + (M_d / M_a^2)^2 s_a^2$  (4.19) Where  $s_s^2 = variance of dry solids measurement$   $s_a^2 = variance of ash solids measurement$  $= \pm 0.002 g$ 

The average  $s_{MCwb}$  for 75 moisture content (% wb) determinations with measurement error variance of ± 0.001 g is 2.26 % wb moisture content. Table 4.10 summarizes the results for six measurements selected to cover the typical range of dry solids mass and moisture contents encountered in the experiment.

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The average standard deviation of volatile solids (total solids basis) was much higher than that for  $MC_w$ : 7.0 percent volatile solids. Four place accuracy in weighing is necessary to assure the same level of accuracy in volatile solids measurements as is achieved with 3 place accuracy of moisture content determinations.

Wet Solids	Dry Solids	M <sub>w</sub>	Md	s <sup>2</sup>	S
(g)	(g)	(१)	(%)		
1.447 2.345 0.881 2.232 1.141 1.623	0.394 0.701 0.307 0.659 0.316 0.481	78.6 77.0 74.2 77.1 78.3 77.1	586 334 287 339 361 337	29.4 7.7 34.6 9.3 44.5 17.4	54.2 27.8 58.8 30.5 66.7 41.7

Table 4.10: Sensitivity analysis for moisture content expressed on an dry solid basis.

Table 4.11 summarizes the results for six volatile solids content measurements selected to cover a typical

Table 4.11: Sensitivity analysis for volatile solids expressed on a dry and ash solids basis.

Dry Solids	Ash Solids	VS	vs <sub>a</sub>	s <sup>2</sup>	S
(g)	(g)	(१)	(%)		
0.307 0.461 0.672 0.415 0.481 0.338	0.044 0.083 0.153 0.087 0.073 0.051	85.7 82.0 77.2 79.4 84.8 84.9	598 456 339 385 559 563	5130 925 374 628 1670 3450	716 304 193 250 408 588

range of ash mass and volatile solids. In some cases the standard deviation of the measurement is larger than the measurement itself. The use of scales accurate to  $\pm 0.001$  mg is necessary to achieve reasonable accuracy.

### 4.8 Bulk Density

## 4.8.1: Calculations

Bulk density was calculated using the "cylinder" method. The equation used in this calculation was:

$$\rho_{\rm b} = M_{\rm net} F / \pi r^2 h$$
 (4.20)

The method used to obtain quantities necessary for bulk density determination has been partially described in the core sampling section. The length of the sample was determined by measuring its furthest penetration depth, and subtracting that from the penetration depth of the previous sample. A colored scale on the corer was used to take initial length measurments. This was immediately confirmed with a finer scale. Values were accurate to ± 1/8 inch.

The net mass of the compost material was calculated as:

 $M_{net} = M_{ls} + M_{ss} - M_b \qquad (4.21)$ where ls = large sample weight, g ss = small sample weight, g b = bag weight, g

### 4.8.2: Sensitivity Analysis

The variance of bulk density due to measurement errors can be broken down into four areas: net weight of solids, moisture content, effective core height and effective core radius. Variance due to the net mass of the solids is additive:

 $s_{M}^{2} = s_{1s}^{2} + s_{ss}^{2} + s_{b}^{2}$  (4.22)

where the terms are as defined previously. For the analytical balance used, all variances were  $\pm$  0.001 and  $s_{net}^2$  equals  $\pm$  0.003. Moisture content errors have been analyzed previously.

The effect of errors in length measurement on the percent volume variance is shown in Figure 4.13. This is based on the following calculation:

 $s_{Vol}^2 / Vol^2 = [(s_h h)^2 + (s_r 2r)^2 (4.23)]$ where Vol = volume of sample, m<sup>3</sup>

From these data it can be seen that height does not greatly affect volume. Small volumes are more sensitive to errors than larger volumes.

Radius errors effected volume variance to a much greater degree than errors in height. Figure 4.14 shows the effect of changes in radius variance from  $\pm$  1/8 to  $\pm$  5/16 inches. The previous equation for variance was used in this calculation as well.

Turning to the bulk density measurement, the partial derivative of bulk density with respect to weight is given by

 $\partial \rho_b / \partial W_{net} = (1 / \pi r^2 h)$  (4.24) where the terms are previously defined. This shows that the rate of change of bulk density with respect to weight is a constant.

The partial derivative of bulk density with respect to sample height is

 $\partial \rho_b / \partial h = -\rho_b / h^2$  (4.25)



Figure 4.13: Effect of length errors on total variance as a percent of total volume.



Figure 4.14: Effect of changes in radius variance on total variance as a percent of total volume.

Changes in bulk density due to height vary with the inverse of the square of the height.

The partial derivative of bulk density with respect to sample radius is

$$\partial \rho_{\rm b} / \partial r = -2 \rho_{\rm b} / r^3$$
 (4.26)

Errors in bulk density with radius variations vary inversely as the cube of the radius.

Figure 4.15 shows the effect of two different radius errors on bulk density. The fractional variance equation used for this calculation is

$$s\rho_{b^{2}} / \rho_{b^{2}} = W^{2} S_{w^{2}} + 4 s_{r^{2}} / r^{2} + s_{h^{2}} / h^{2}$$
 (4.27)

The relative contributions of various measuring errors on bulk density are shown in Figure 4.16. Figure 4.17 shows the total, radius and height percent variances. Percent variance due to radius measurement errors makes up most of the total percent variance. Errors due to weighing and moisture content are smaller than that for core height.

While this analysis is generally correct, it does not account for errors from several sources. First, if the core does not travel in a straight line as it goes into the windrow, larger effective volumes may be sampled. Secondly, the effective radius may be larger or smaller than the interior core head radius because of compost particles from outside or inside this radius being pushed out or pulled into the sample. Vibration of the core may shift some compost material out of the sampler. The effect of core



Figure 4.15: Effect of two different radius errors on total variance as a percent of bulk density measurements.



Figure 4.16: Relative contribution of various sources of error to total variance as a percent of bulk density measurements.



Figure 4.17: Relative contribution of radius and height errors to total variance as a percent of bulk density percent measurement.

rotation speed on these errors is also not described.

# 4.9: Porosity and Free Air Space

## 4.9.1: Calculations

Porosity and free air space can be calculated with the results of the moisture content, bulk density and volatile solids content. The general equation for these calculations is:

 $f_x = 1 - (\rho_b / \rho_s)$  (4.28)

where  $f_x = porosity$  or free air space  $\rho_b = wet$  bulk density, kg/m<sup>3</sup>  $\rho_s = particle$  density, wet or dry, kg/m<sup>3</sup>

Based, in part, on work by Bohnhoff et al. (1984), the particle density used in porosity determinations is:

$$\rho_{sd} = (A - B VS) / (100 - MC_{wb})$$
 (4.29)  
where  $\rho_{sd} = particle density, dry, kg/m^3$ 

A and B are the parameters of a linear regression of volatile solids content vs. DMS particle density from three dairies with different separators and rations. These values are given in Table 4.12.

Table 4.12: Values of constants A and B from dairy manure solids specific gravity measurements.

	Source	A	В
Farm 1	(Centrifugal)	232000	814
Farm 2 Farm 3	(Stationary screen) (Perforated drum/	235600	868
	compressing roller)	200600	473
Average		227800	773

Source: Bohnhoff et al. (1984)

Bohnhoff et al. (1984) presented the following formula for particle density to be used in determing free air space:

$$\rho_{\rm sm} = [(A - B VS) / (100 - MC_{\rm wb}) + (10^{5} / MC_{\rm wb})] \qquad (4.30)$$

where  $\rho_{DM}$  = particle density, moist, kg/m<sup>3</sup>

Equations 4.23 and 4.24 are substituted into Equation 4.22 for the calculation of porosity and free air space, respectively.

 $f = 1 - \rho_b * (100 - MC_{wb}) / (A - B VS)$ (4.31)  $f_a = 1 - \rho_b * [(100 - MC_{wb}) / (A - B VS)]$  +  $(MC_{wb} / 10^5)$ ] (4.32)

where f = porosity, decimal f<sub>a</sub> = free air space, decimal

and all terms are as previously defined.

# 4.9.2: Sensitivity Analysis

Variance due to measurement errors was analyzed in a manner similar to that of the previous sections. The effects of sample weight, sample radius and height, moisture content and volatile solids were considered. The effects of changes in the parameters A and B were also examined.

The partial derivatives of porosity with respect to the various factors are shown in Table 4.13. The partial derivatives with respect to bulk density, weight, and moisture content are all linear. The partial derivatives with respect to radius and height are similar to those for bulk density, varying with the cube of radius and the square of height, respectively. The partial derivatives of porosity with respect to the volatile solids and factors A and B are not linear but change with the volatile solids, A or B being divided by the square of the term (A - B\*VS).

The equation used to estimate the total variance in porosity is given below:

$$s_{f}^{2} = [(C/Vol)^{2} * s_{M}^{2} + (\rho_{b} C/h)^{2} * s_{h}^{2} + (2 \rho_{b} C/r)^{2} * s_{r}^{2} + (\rho_{b}/(A-B*VS))^{2} * s_{M}Cwb^{2} + (\rho_{b}*A/(A-B*VS)^{2})^{2} * s_{A}^{2} + (\rho_{b}*B/(A-B*VS)^{2})^{2}) * s_{B}^{2} + (\rho_{b}*V/(A-B*VS)^{2})^{2} * s_{V}^{2}$$
where C = (100 - MC<sub>wb</sub>) / (A - B VS)

Table 4.13: Partial derivatives of porosity calculation.

 $f = 1 - \rho_{b} * \left( 100 - MCwb \right) = 1 - (M / \pi r^{2} h) * (C)$   $\frac{\partial f}{\partial \rho_{b}} = - (C)$   $\frac{\partial f}{\partial M} = - (C) / \pi r^{2} h$   $\frac{\partial f}{\partial h} = (C) / \pi r^{2} h^{2}$   $\frac{\partial f}{\partial h} = 2 W (C) / \pi r^{3} h$   $\frac{\partial f}{\partial T} = \rho_{b} (1 / A - B VS)$   $\frac{\partial f}{\partial A} = -\rho_{b} (-B / (A - B VS)^{2})$   $\frac{\partial f}{\partial B} = -\rho_{b} (VS / (A - B VS)^{2})$ 

The variances contributed by each of the factors of porosity variance are shown in Table 4.14. Three levels of variance for each factor were used; they were labeled Low, Medium and High. The above equation was applied to 75 porosity measurements. The porosity variances presented in the following figures are given in terms of actual porosity

Table 4.14: Error levels of contributing factors to porosity and free air space variance.

Error Source	Low	Error Level Medium	High	
Net Mass (g)	±0.001	±0.01	±0.1	
Core Height (in)	±0.125	±0.250	±0.375	
Core Radius (in)	±0.125	±0.250	±0.375	
Moisture				
Content (% wb)	±1	±5	±10	
Factor A	±10	±500	±1000	
Factor B	±1	±50	±100	
Volatile				
Solids (%)	±1	±5	±10	

values and not as a percent of the actual porosity.

The total porosity variance for the different variance levels is shown in Figure 4.18. For all three error levels, 80 percent of all measurements had variances less than 2 percent porosity. The higher variances occurred with the lower porosity readings. These corresponded almost entirely to the deepest samples in the center of the windrow. One characteristic of these samples was that they were typically one-half the length of other samples due to the length of the core sampler. It is also interesting to note two linear regions in the data, one that corresponds to



Figure 4.18: Total porosity variance for 3 levels of factor variance.

porosities of 95 percent and greater and the other corresponding to porosities between 90 and 95 percent.

Closer examination of the high error case shows the contributions of several factors to the total porosity (Figure 4.19). Variance in determination of Factor A contributes almost all of the variance in porosity with the radius variance coming in a distant second. The effect of errors in the measurement of Factor B, height, moisture content, volatile solids and weight are almost negligible. Factors A and B arise from a linear regression of volatile solids data to determine the specific gravity of the solids that was done by Bohnhoff et al. (1984). This measurement was not part of the current research. Given the sensitivity



Figure 4.19: Contributions to total porosity variance due to high factor variance.

of porosity to Factor A, this measurement should be performed in future work of this nature.

The partial derivatives of the free air space with respect to the various factors are shown in Table 4.15. The results are similar to those for porosity with a slightly different product. The partial derivatives with respect to bulk density, weight, and moisture content are all linear. The partial derivatives with respect to radius and height vary with the cube of radius and the square of height, respectively. The partial derivatives of porosity with respect to the volatile solids and factors A and B are not linear but change with the volatile solids, A or B being divided by the square of the term (A - B VS).

Table 4.15: Partial derivatives of free air space calculation.

 $f_{a} = 1 - \rho_{B} * (100 - MCwb + MCwb) = 1 - (W / \pi r^{2} h) * (D)$   $A - B VS = 10^{5}$   $\frac{\partial f_{a}}{\partial \rho_{b}} = - (D)$   $\frac{\partial f_{a}}{\partial M} = - (D) / \pi r^{2} h$   $\frac{\partial f_{a}}{\partial h} = (D) / \pi r^{2} h^{2}$   $\frac{\partial f_{a}}{\partial h} = 2 W (D) / \pi r^{3} h$   $\frac{\partial f_{a}}{\partial M} = -\rho_{b} (-1 + 1/10^{5})$   $\frac{\partial f_{a}}{\partial A} = -\rho_{b} (-A / (A - B VS)^{2})$   $\frac{\partial f_{a}}{\partial B} = -\rho_{b} (VS / (A - B VS)^{2})$ 

The equation used to estimate the total variance in free air space is given below:  $s_{fa}^2 = [(D/Vol)^2 * s_M^2 + (\rho_b D/h)^2 * s_h^2 + (2 \rho_b D/r)^2 * s_r^2 + (\rho_b * [(1/(A-B*VS))+1/10^5])^2 * s_{MCwb}^2$ 

+ 
$$(\rho_{b}*A/(A-B*VS)^{2})^{2} * s_{A}^{2}$$
 +  $(\rho_{b}*B/(A-B*VS)^{2})^{2}) * s_{B}^{2}$   
+  $(\rho_{b}*VS/(A-B*VS)^{2})^{2} * s_{VS}^{2}$  (4.34)

where D =  $((100 - MC_{wb}) / (A - B*VS)) + MC_{wb} / 10^{5}$ 

Free air space values have a much greater range than porosity: 35 to 87 percent. Variance due to errors in measurement are also much greater than those for porosity, with the maximum variance for each error level being 19, 11.5 and 4.5 percent free air space for the high, medium and low levels, respectively. This is shown in Figure 4.20, free air space total variance. Contributions of various factors to free air space total variance are somewhat different with errors in radius measurement being larger than errors in the measurement of Factor A (Figure 4.21). Errors in the measurement of other factors are negligible.

## 4.10: Additional Physical Properties

A number of other physical and moisture related parameters can be calculated from the results of the bulk density, porosity and free air space calculations. These parameters can provide additional insight into the internal state of the windrow.

Gravimetric moisture content provides information on the weight of water present in a given windrow volume, which is important for calculating specific heat. The relative



Figure 4.20: Total free air space variance for 3 levels of factor variance.



Figure 4.21: Contributions to total free air space variance due to high factor variance.

weight of water, as opposed to that for the dry DMS, can mask important differences in the relative volumes of air, water and solids. Volumetric moisture content presents information on the volume of water present in a unit area. The volumetric moisture content can be calculated by

$$\theta = M_{wb} \rho_b / \rho_w \qquad (4.35)$$

where  $\theta$  = Volumetric moisture content, decimal  $\rho_w$  = water density, kg/m<sup>3</sup>

If the values of porosity and free air space are known, θ can be calculated as follows:

$$\theta = f - fa \qquad (4.36)$$

The volumetric solids content can similarly be calculated by

$$f_s = 1 - f_a$$
 (4.37)

where  $f_s =$  volumetric solids content, decimal

The void ratio relates the volume of the void to the volume of solids. The definition is given as follows:

 $\epsilon = (v_{air} + v_w) / v_d = v_p / (v_t - v_p) (4.38)$ where  $\epsilon =$  void ratio, decimal  $v_x =$  volume of x
air = air w = water p = pores t = total

Void ratio can also be calculated from the relationship

$$\epsilon = (1 - f) / f$$
 (4.39)

where f is the decimal porosity. Equation 4.35 will be used in this study.

The degreee of saturation, that is, the volume of void space occupied by water, is calculated as follows:

 $s = v_w / v_p = v_w / (v_{air} + v_w)$  (4.40) where s is the decimal degree of saturation. The degree of saturation can also be calculated by

$$s = 1 - (f_a / f)$$
 (4.41)

Equation 4.37 will be used in this study.

## 4.11: Windrow Size Changes

Windrow size and shape changes were measured by two methods. The main observations were made by measuring the distance from the windrow surface upward to a grid of equally spaced co-planar wires stretched horizontally over the windrow. Before each set of measurements was taken, the height of the wire at the center was standardized by adjusting wire tension. The distance between the grid and windrow surface was determined by holding a plumb bob at the grid location and measuring the distance between the wire and the point on the windrow surface that the plumb bob touched. Thirty or 36 locations were measured in this manner on the 1st, 3rd, 5th and 7th days after the windrow was turned. The distance from the top of each probe to the top of the surface next to the probe was also measured. All probes touched the floor. Measurement error was  $\pm 1/8$  inch. Only one side and the top of the windrow were measured by this method.

#### CHAPTER 5

#### EXPERIMENTAL RESULTS

### 5.1: General Observations

Two windrows were monitored: one in the summer and one in the fall of 1986. Windrow turnings are designated A, B, and C. Ambient conditions during the summer windrow (Windrow 1) were generally warm and humid. The fall windrow (Windrow 2) was preceded by cold and wet weather. Data on ambient weather conditions are presented in Figure 5.1. Ambient temperatures rose during the first week of Windrow 2 but the overall weather was colder and rainier than for Windrow 1. Due to difficulties in correctly programming the relative humidity sensor, one third of these data were not collected.

## 5.2: Windrow Size and Shape

Windrow size and shape varies between windrows and turnings. Figure 5.2 shows the cross-sections of Windrows IA and 2A. The changes between windrows were due to the amount of material in the windrow: Windrow 2 had half again as much material as Windrow 1. A summary of windrow weight and sizes is given in Table 5.1. Differences that occur when a windrow is turned are due to difficulties in constructing successive windrows to exactly the same shape







Figure 5.2: Cross-sections of Windrows 1A and 2A.

Tabl	e	5.1	:	Summary	of	wind	lrow	weight	and	size.
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Windrow	Weight	(kg)	Area <sup>a</sup>	Volume <sup>a</sup>	Bulk Density <sup>a</sup>
	Initial	Final	(m <sup>2</sup> )	(m <sup>3</sup> )	(kg/m <sup>3</sup> )
1A 1B 1C	5440 3320 3650	3320 3650 na	3.32 1.82 1.82	15.2 7.57 9.23	360 440 395
2A 2B 2C	7500 <sup>b</sup> 6300 5740	6300 5740 4900- 5300 <sup>C</sup>	2.82 2.37 2.44	12.9 10.8 11.1	580 580 520

a Calculated for initial conditions.

b Total amount weighed = 8860 kg. Aproximately 1360 kg not used.

C Rain occurred during weighing. Difference reflects amount of wetter material added. and size and to material lost in the composting process.

Windrow size changes during each of the turning periods. Figure 5.3 is a topographic representation of the front half of Windrow 1B. The windrow is quite uniform with a slight rounding at the edges. Changes in Windrow 1B after 1 week of composting are shown in Figure 5.4. A crosssectional view of average values for the same time period is given in Figure 5.5. The center height decreases during each windrow turning, in this case by about 2 to 3 inches. The height of the upper part of the slope decreased slightly while the lower face height increases slightly. These changes are as much as 10 percent, but are typically 2 to 3 percent of windrow height at a given location. Windrow elevation data availability are discussed in Appendix H.

The location of monitoring points varies between windrows and with the parameter being monitored. All temperature/gas sampling probes were inserted into the windrow until they touched the compost bin floor. Since windrow size and shape varies between windrows and turnings, the distance between monitoring points and the windrow surface also varies. This is true for both the distance betweeen the monitoring point and surface (Figure 5.6) measured along the probe and at right angles to the surface. See Appendix H for information on the availability of data on the location of the monitoring points. Due to initial windrow sizes and changes in windrow size during the composting period, sampling points could be exposed and give











Figure 5.5: Cross section of Windrow 1B elevation changes.



Figure 5.6: Cross section of windrow showing distances from a monitoring point to windrow surface along the probe (Dp) and the nearest surface point (Ds). temperature or gas concentration readings that reflected ambient conditions.

#### 5.3: Temperature

## 5.3.1: Temperature Variablity

A key assumption of the experiment is that the windrow is long enough so that transport processes along the length of the windrow can be neglected. While this assumption was not directly tested, data from Windrow 2 can be used to assess whether the three replications of the 9 locations were measuring the same phenomena. Because of the small sample size (1 for each turning) it is hard to draw conclusions about variability in temperature by location.

The variance of temperature between the three replications of each location is calculated for each 15 minute average temperature for the three turnings of Windrow 2 and are shown in Figure 5.7.

Windrows 2A and 2C exhibited average variances within the experimental measurement variance of  $\pm$  1.5°C with the exception of 1 point in each windrow. Windrow 2B exhibits rather large average variances, with 6 of the 9 points having variances larger than the variance due to instrument error.

An analysis of the patterns of variability proved instructive. If there is a longitudinal effect, one would expect the left (L) and right (R) replications to be closer together than L and the center (C) or R and C. Longitudinal effects are assumed to be present if the difference between

	Windrow 2A				Windr	ov 2B		Windrov 2C			
		56.6	56.5			54.7	57.3			58.0	57.3
47.6	57.6 46.1	50.0 35.6	43.1	39.6	52.5 58.3	62.Z 49.8	52.5 42.8	42.1	57.4 57.9	60.9 49.6	52.5 42.8
				Avera	ge Temp	erature	(°C)				
		0.14	0.34			1.66	0.19			0.55	0.74
A 7A	0.99	0.05	0.23	1 40	3.51	2.96	2.17	7 15	0.76	0.17	0.42
					Varianc	e (°C)					
		0.64	0.88 l			2.03	0.74			1.26	0.33
	1.43	0.47	1.09		3.63	2.18	2.59		1.68	0.68	0.93
.75	3.41	1.45	0.84	1.79	0.63	3.42	2.11	4.99	1.55	1.69	1.72
					Z Tine (	Same Si	gn				
	ы	N	Ľ I		v	Y	N		Ν	Ŷ	Ŷ
N	N	n N	Ň	ж	T Y	л Х	Y	к	א	T N	T Y
			ليتنب	Sin	nilar SI	naped Co	Jrve				

Figure 5.7: Measurements of temperature variability in Windrow 2.

C & L and C & R showed the same time-temperature pattern and the percent of time that they were the same sign. Figure 5.7 shows these results.

Windrow 2A is low by both measurements, with same sign differences present at only 46 percent of the time and only 2 of 9 locations having similar patterns. Windrow 2B has 4 locations with similar patterns and the differences have the same sign 79 percent of the time. Windrow 2C has the highest number of locations with similar patterns; 72 percent of the time the differences have the same sign. No pattern is obvious: Windrow 2B has high values of this parameter and variance while 2C has slightly higher values but low variance. This is also true for the number of locations where temperature differences were judged to have the same shape.

Based on Windrow 2A and 2C, it appears that the longitudinal variability is negligible. Due to higher variability in Windrow 2B and the effect of ambient conditions on the composting process, however, this conclusion must be tested further. In addition to measurement errors, there is also the effect of the probe placement to be considered. While each probe was placed so that the locations were approximately the same in the y-z plane, it was not always possible to achieve this. Thus, differences in y-z plane location could affect the measured temperature variability. It is also possible that the higher variance in temperature is due to the presence of

different transport processes in the windrow, i.e. natural convection as opposed to diffusion. Nonetheless, for purposes of analysis, the replications will be considered to be averageable.

#### 5.3.2: Temperature Patterns

The maximum temperature in either windrow is 68°C; most of the windrow tend to be in the 45°C to 55°C range. Temperatures near 35°C are seen deep in the center and at the outer edge of the windrow early and late in the runs, respectively.

Temperature profiles are shown in Figures 5.8 through 5.10, for Windrow 1. Temperatures in locations near the surface, 1, 2, 4, and 8, are initally high and either rose to a near constant level (Location 8 in Windrow 1A, Figure 5.10) or peak and fall off (Locations 1, 2, and 3 in Windrow 1B, Figure 5.8). Towards the end of a given turning, the surface temperatures tend to reflect ambient conditions. This could be due either to an actual reduction in respiration in those areas of the windrow or in the case of locations 8 and 4 (Figures 5.10 and 5.9), due to the thermocouples becoming exposed late in the runs.

Locations deeper in the windrow such as 3, 5 and sometimes 9, show either the same pattern as the the surface temperatures, i.e. a rise, plateau and slight fall (Locations 3 or 5 in Windrow 1C), or develop in an "S" type pattern (Location 3 in Windrow 2A). Locations 6, 9, and 10 tend to exhibit mainly the "S" type temperature profile



Figure 5.8: Temperature profiles for Locations 1, 2, and 3, Windrow 1.



Figure 5.9: Temperature profiles for Locations 4, 5, and 6, Windrow 1.



Figure 5.10: Temperature profiles for Locations 8, 9, 10 and Slab, Windrow 1.

(Location 6 in Windrow 1A).

The temperature profile in the windrow at any given time can yield important information on the locations in the windrow that reach a given temperature. Cross-sections of Windrow 1A taken at noon on days 1, 3, 5, and 7 are shown in Figures 5.11 through 5.14 for illustration. Figure 5.15 presents the same information for day 7 of Windrow 2C. Since temperature was not measured on the windrow surface or in the front of the toe area and since the thermal properties of the compost and air are different, assumptions about the temperature in those areas had to be made. The five Figures (5.11 to 5.15) are good for illustrative purposes only and do not reflect the actual temperatures at







Mindrow Height

(up 'Z)

Temperature (°C) profiles for Windrow lA cross-section on Day 3 at noon.



Windrow Height (Z, cm)




(то , с) элріэн мольпім







the toe and surface.

In general, the temperature profile of a given windrow tends to have the highest temperatures at some distance from the surface, with slightly lower temperatures at the surface and much lower temperatures deep in the interior of the windrow. With time, the zone of higher temperatures moves inward and the edges cool.

### 5.3.3: Time-Temperature Relationships

A key parameter in predicting the thermal death of pathogenic micro-organisms is the length of time a microbial population remains at lethal temperatures. Table 5.2 summarizes the time-temperature data for locations monitored in Windrow 1. Similar data for Windrow 2 are presented in Table 5.3. Figures 5.16 through 5.21 show the length of time that a given location remains in a given temperature range for Windrows 1 and 2.

# 5.4: Gas Concentrations

Concentrations of oxygen and carbon dioxide were initially calculated using the method described in Chapter 4, unmodified. Examination of the data, however, indicates higher oxygen concentrations than expected in the interior of the windrow (Location 10, Figure 5.22). Under forced air composting, oxygen depletion is very rapid and quickly falls to levels of 1 or 2 percent. While the DMS composting system is not expected to produce such a quick reduction in oxygen concentration, because of the length of time between turnings, oxygen levels are expected to be in the same

			Lei	ngth of	f Time	(days	)	
Location			Temp	peratu	re Rang	e (°C	:)	
	30-35	35-40	40-45	45-50	50-55	55-60	60-65	<b>65-</b> 70
Wind	lrow 1A	<u>\</u>			Total	Time:	6.96	days
1 2 3 4 5 6 8 9		3.15 1.74	2.56 0.65 1.34 0.52 0.89	$\begin{array}{c} 0.35 \\ 0.49 \\ 0.88 \\ 1.24 \\ 0.44 \\ 1.42 \\ 0.46 \\ 0.81 \\ 1.20 \end{array}$	1.74 0.47 0.77 0.70 2.46 1.01 1.40	2.62 1.57 1.61 1.12 4.97 3.86	2.25 4.43 3.71 4.09	
Wind	lrow 1E	3.10	2.40	1.50	Total	Time:	6.88	days
1 2 3 4 5 6			1.50	1.44 0.30 0.39 2.11 0.65 2.98	2.28 0.28 1.09 2.27 0.56 2.04	2.70 2.99 2.38 0.72 1.47	0.47 3.31 3.03 1.33 0.40	3.62
8 9 10			1.69	0.35 0.35 2.15	6.53 0.99 2.74	2.79 0.30	2.75	
Wind	lrow 10	-			Total	Time:	6.81	days
1 2 3 4 P	2.38 Probe e	1.73 1.71	1.22 2.24 2.63	1.49 1.88 1.84	0.99 2.34			
5 6 8 9		0.22	6.59 0.72	0.24 1.34 0.49 0.88	0.27 0.74 4.81	0.62 1.00 0.80 2.84	5.68 3.73	

Table 5.2: Time-temperature data for monitoring locations in Windrow 1.

				1	Length	of Tir	me (da	ays)	
Lo	cation			Т	emperat	ture Ra	ange	(°C)	
	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70
	Wi	indrow	<u>2A</u>			Tot	tal Tir	n <b>e:</b> 5	.80 days
1 2 3 4 5 6 8 9 10	1.26 1.13 25-30	0.98 0.01 1.51 0.52 3.38 30-35	0.19 1.00 0.86 1.45 1.33 1.29 35-40	0.68 0.08 0.71 0.10 0.74 1.58 0.09 1.35 40-45	3.27 0.45 0.52 0.42 0.86 0.59 2.28 45-50	1.67 0.73 1.21 0.58 1.29 0.66 0.31 50-55	1.92 1.38 4.70 2.03 4.46	2.62	65-70
	Wi	indrow	<u>2B</u>			Tot	tal Tin	ne: 6.	842 days
1 2 3 4 5 6 8 9 10		0.01	5.12 0.08 0.06 0.15 2.36	1.20 0.06 0.26 0.06 0.14 2.29 0.21 1.34 2.85	0.51 1.83 0.15 0.18 0.56 1.28 0.32 1.18 1.62	2.22 0.12 2.79 0.67 1.67 0.59 1.51	2.00 2.99 3.72 1.06 1.54 5.71 2.38	0.65 3.32 1.01	3.41
	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70
	Wi	Indrow	<u>2C</u>			Tot	al Tin	ne: 6.	88 days
1 2 3 4 5 6 8 9 10			2.38	2.66 0.26 0.54 2.26 0.11 2.15	1.83 0.19 0.31 0.28 0.55 1.40 0.29 1.84 3.85	1.56 0.40 0.52 0.57 1.56 0.55 1.08 0.88	3.74 2.89 6.07 0.90 1.66 4.72 1.96	1.46 2.84 1.34 1.31 1.88	2.97

Table 5.3: Time-temperature data for monitoring locations in Windrow 2.





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1-1-1-1-2-2.

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Figure 5.22: Gas concentrations at Location 10 showing suspect high oxygen levels.

range.

The experimental methods used in the gas sampling and analysis were re-examined as described in Chapter 4. In the course of this examination, it was found that ambient gases could have entered the sampling syringe. This was probably due to gas flowing into the syringe needle because of either diffusion or a pressure differential between the syringe body and the ambient air. The effect of calculated internal sample bottle pressure on the percent influx into the syringe was studied and a calculation procedure was derived to correct for this, based on the number of samples that had been withdrawn from the sample bottle. The effect of leakage during several weeks' storage time was found to be negligible, although further work in this area is necessary.

The difference between original and corrected oxygen data is shown in Figure 5.23 for selected data.

The gas concentration data are presented in Figures 5.24 through 5.27. These data represent the average values for each location. Several trends are present in this data. At any given time, locations near the surface (Locations 1, 2, 4, and 8) have higher oxygen and lower carbon dioxide concentrations than those in the center (Locations 6, 9, 10, and sometimes 5 and 3). This is shown in Figure 5.28.

Over time the relationship between carbon dioxide and oxygen depends on the location. Near the surface carbon dioxide starts high and decreases over time, while oxygen concentrations do the inverse (Location 1, Figure 5.29).



Figure 5.23: Difference between original and corrected oxygen concentration for selected data.

	10.23 1.29 2.28	14.88 1.42 1.95	20.69 6.41 5.07	
Day 7	16.98 5.42 5.89	15.50 6.32 7.69	11.84 6.37	
-	16.13 7.33	16.86 12.31	20.77 19.21	
	16.87	18.34	21.20	for
	9.98 3.08 4.18	12.63 2.09 3.31	21.36 16.18 16.37	data
Day 5	15.98 5.64 3.52	15.44 3.29 1.26	18.40 18.12	ion
-	16.53 10.33	15.32 4.67	20.90 20.19	ntrat
	16.94	16.54	21.19	oncer
	3.65 10.60 5.12	10.45 3.03 2.35	19.86 -0.43 -4.01	den o
Day 3	17.06 5.31 4.10	13.12 2.46 1.25	11.77 1.21	0×0
_	11.65 5.46	13.30 2.75	18.70 15.30	24:
	10.35	13.84	19.82	re 5.
	9.04 6.46 9.84	9.90 2.14 4.68	16.16 1.38 2.76	Fian
lay l	16.21 4.93 4.73	13.74 2.74 5.25	19.89 4.13 2.59	
-	10.29	6.17 3.61	14.43	
	5.87	7.59	18.97	

Figure 5.24: Oxygen concentration data f Windrow 1.

	2.43 0.84 1.54	6.20 2.63 1.48	9.60 2.05 3.31
Day 7	6.96 1.15 0.78	0.52 7.68 0.64	10.26 4.38 3.93
_	9.92 1.56	18.18 14.34	17.91 13.75
	18.16	20.64	20.57
	2.08 1.87 3.59	8.04 2.70 1.18	6.96 2.45 14.73
Day 5	5.69 2.12 0.98	13.77 6.77 3.71	9.60 3.28 2.13
	8.99 1.16	17.07	16.84 11.10
	16.91	19.06	19.31
		4.65 3.18 0.83	6.23 1.89 1.23
ay 3		8.99 2.41 3.09	6.54 1.57 2.18
		13.97 9.03	15.83 4.44
		18.77	18.03
		2.12 2.12 2.12 1.44	3.60 1.55 2.11
ay 1		5.26 2.55 1.28	4.45 1.48 1.79
0		10.71 2.82	10.64 3.38
		18.93	17.63

Figure 5.25: Oxygen concentration data f Windrow 2.

.

	11.62 19.55 19.49	6.78 18.31 19.88	0.56 16.16 17.28
Day 7	4.10 14.81 15.89	5.91 13.47 12.70	10.44
	<b>4.8</b> 2 12.81	3.90 8.45	1.03
	4.12	2.61	0.93
	14.29 21.21 20.99	10.41 18.94 18.69	0.44 6.06 6.62
Day 5	6.97 17.56 20.77	6.35 16.79 19.33	3.50
	5.06 11.88	5.39 15.21	0.34
	6.34	4.40	0.63
	19.96 12.91 18.51	11.22 18.02 20.80	1.04 14.67 17.09
Day 3	6.40 18.48 21.36	7.93 16.89 19.44	6.56 13.26
_	11.43	7.52 16.53	1.41 4.34
	11.79	6.64	1.63
	13.38 16.45 14.55	11.62 18.87 17.77	4.15 19.52 19.11
Day 1	6.19 17.65 21.48	8.62 18.11 17.82	0.55 16.87 20.31
_	12.12 19.94	14.50 18.88	6.70 12.80
	16.47	13.66	1.94

concentration data	
Carbon dioxide	for Windrow 1.
Figure 5.26:	

	20.02 21.83 22.24	15.94 19.08 21.59	11.32 21.53 21.02
uay /	16.20 21.52 22.62	20.81 12.90 20.59	11.72 16.22 17.34
	11.49 20.49	2.21 6.98	3.06 6.90
	3.07	0.85	0.54
	20.04 21.75 21.57	11.85 17.35 20.00	15.81 21.12 7.67
~ (=_	15.51 21.08 23.98	4.50 11.39 15.45	10.99 17.76 19.93
	11.71 21.22	1.67 7.34	3.81 9.58
	4.95	-0.06	0.63
		18.48 21.20 21.87	16.24 20.92 24.38
		12.92 19.26 17.60	15.69 19.70 21.47
		4.94 12.21	5.20 16.34
		1.19	0.96
		21.24 21.24 23.34	18.58 22.86 23.14
		18.54 22.34 23.63	18.32 22.42 23.50
-		10.84 20.03	10.98 20.04
		1.71	2.56

Carbon dioxide concentration data for Windrow 2. Figure 5.27:



Figure 5.28: Gas concentrations by location, Windrow 1B, Day 3.



Figure 5.29: Gas concentrations over time, Location 1. Lines indicate general trends in data, not intermediate values.

There is a partial recovery towards the initial concentration after the windrow is turned but the pattern then repeats itself. Locations in the middle zone (3 and 5, Figure 5.30) show much longer durations of high carbon dioxide or low oxygen than those near the surface. Locations 6, 9 and 10 consistently show high carbon dioxide and low oxygen for the duration of the composting (Figure 5.31).

Some gas samples from Locations 9 and 10 taken during Windrows 2B and 2C were analyzed for methane concentration. Low concentrations of between 0.5 % and 1.5 % methane were found. This result suggests that future studies include methane analysis as a means of more accurately determining the windrow reaction and transport processes.

### 5.5: Moisture Content

Drying of the windrow surfaces was evident within a few hours after windrow formation. The compost material turned light brown, almost white, as it dried. The greatest penetration of the dry layer was only 0.5 to 1.0 cm, however. Blooms of small mushrooms appeared between 3 to 5 days after each windrow turning.

Figures 5.32 and 5.33 present the wet basis moisture contents (% wb) by location for Windrows 1 and 2, respectively. Figure 5.34 shows the average moisture content by location for each turning.

Moisture content remains essentially constant over the 3 week duration of each windrow, decreasing from



Figure 5.30: Gas concentrations over time, Location 3. Lines indicate general trends in data, not intermediate values.



Figure 5.31: Gas concentrations over time, Location 10. Lines indicate general trends in data, not intermediate values.

	78.7 77.7 78.7		77.3	77.1	77.8		76.7	76.9	77.6
	80.0 78.6 78.3		77.8	77.4	77.4			17.6	77.2
	79.9 79.2			78.2	78.0			76.8	77.4
	78.6 80.0			78.4	79.5				77.3
	80.0 79.0 80.0		78.3	11.4	78.5		77.1	9.11	78.1
1A	80.6 79.6 79.6	18	77.3	77.2	77.3	21	77.1	77.8	1.1
Nindrov	79.8 80.2	Vindrov		77.6	1.1	Vindrov		77.8	77.6
	79.0 80.5			76.7	78.0				76.9
	80.0 80.5 80.0		78.8	79.4	78.8		77.3	78.6	78.0
	80.5 80.8 80.3		78.6	78.8	1.67		77.5	78.6	78.4
	80.1 79.8			78.5	79.0			78.0	77.8
	80.7			78.4	79.2				77.8

Figure 5.32: Gravimetric moisture content (%wb) by location for Windrow 1.

Day 7

Day 3

Day 1

		78.3	76.0		78.0	76.7 77.2		77.6	76.1	1.0		
ay 7		80.7 77.7	77.8		1.9.1	76.6 76.1		78.2	77.0	1.5		
		80.9	95.0			78.8 76.6			77.5	11.2	(dw	•   
			79.3			77.5				1.1	ent (%	
											conte	row 2.
		78.6 76.9	76.1		76.1	81.6 78.1		77.4	77.5	78.2	sture	Wind
ay 3	2 <b>A</b>	82.7 81.9	77.3	28	77.3	76.6 78.0	<b>5</b> C	77.6	77.6	78.1		n for
9	Vi ndr ov	81.9	81.1	<u> </u>		71.7 71.4	Windrov		<b>79.9</b>	1.4	metri	catio
						78.9				1.4	Gravi	by lo
											.33:	•
		81.5 78.5	76.7		78.1	78.1		6.11	78.2	78.4	ure 5	) ) )
t t		81.4 78.5	80.7		78.1	77.7 77.8		78.0	77.6	78.0	Fia	
Δ		80.5	79.6			78.3 78.4		1	77.0	11.6		
			81.2			6.17			;	11.6		

	Wind	rov 1A			Wind	rov 2A	
		80.4	79.6			81.6	79.5
78.8	79.9	79.7	79.1		81.1	79.4	77.1
80.4	79.7	79.4	79.6	53.5	85.2	78.6	76.3
	Wind	rov 1B			Wind	rov 2B	
		77.9	78.1(			78.2	77.4
77.8	78.1	77.8	78.0		78.3	77.0	78.8
78.9	78.2	77.9	78.4	78.1	77.5	77.3	77.9
	Wind	row IC			Wind	rov 2C	
		51.5	77.0			77.9	77.6
	77.5	78.0	77.8		78.1	77.4	77.3
77.3	77.6	77.8	77.9	77.4	77.4	77.9	77.9

Figure 5.34: Average gravimetric moisture content (%wb) by location and turning for Windrows 1 and 2.

only from 81 to 77 % in both windrows. Average standard deviations of the measurements are 2.2 percent. Moisture content sampled after day 1 of each turning tends to have the smallest differences between locations. Samples taken on days 3 and 7 showed a greater range of moisture content. Locations near the surface and base (1 and 2) tended to be the driest in Windrow 1. This pattern is not present in Windrow 2, perhaps due to the accidental flooding with rain.

## 5.6: Volatile Solids

Volatile solids measurements show small decreases within each one-week turning and over the entire three week composting period for each windrow. Figure 5.35 presents the average by location for each turning in Windrows 1 and 2. Figures 5.36 and 5.37 show the volatile solids content

	Windr	ov 1A			Windr	OV 2A	
		94	95			89	85 I
94	95	95	96		87	85	82
95	95	96	96	84	86	86	84
	Windr	ov 18			Windr	ov 2B	
		94	95			83	86
94	94	95	94		83	85	86
94	95	95	64	84	85	87	86
	Windro	ov IC			Windro	ov 2C	
		62	94			82	82
	93	94	94		82	83	84
93	93	94	94	83	83	84	84

Figure 5.35: Average volatile solids content (%db) by location and turning for Windrows 1 and 2.

		5	8 8			95	<u></u>	36			93	35	8
ly 7		5	* %			<b>%</b>	96	R				93	\$
2		8	r 2				2	2				8	¥
		1	5 F				<b>36</b>	2					8
		95	8 8 8			95	36	8			94	93	34
y 3	11	35	% %		Windrov 18	96	94	96	ç	1C 41	63	<b>34</b>	2
Da	<u> </u>		96 36				94	95	-	Alndrov		66	93
			96 36				76	8					8
		95	% %			94	5	8			94	35	5
y 1		95	35 36			35	95	94			93	94	8
Da			<b>2</b> 8				<u>35</u>	95				92	92
			95				<b>94</b>	95					93

location for Windrow 1.

		82	8 2			98	87	86		81	83	8	
y 7		88 88	3 28			81	83	98		81	8	8	
Đ		8	8 8				80	8			80	80	үс
			82					85				83	\$db)
			·										ent ( , 2
		84	85			86	85	85		83	84	84	s cont indrow
IY 3	2A	91 92	81	ec	97	84	86	87	2C	81	<b>84</b>	85	solids for Wi
Da	Windrov	60	88		AD JOU IN		86	88	Windrov		82	84	tile : tion 1
			85					84				83	Vola
													.37:
		90	3 8			86	87	68		83	85	84	jure 5
y 1		68 84	68			85	<b>8</b> 6	87		84	84	83	Fig
Da		84	5 8				8	86			82	æ	
			86					84				8	

.

by location for Windrows 1 and 2, respectively.

The magnitude of the decreases are 2 % and 4 % VS for Windrows 1 and 2, respectively. Due to the volatile solids standard deviation of 7 % VS, however, this is not significant. Differences between the maximum and minimum values of volatile solids in each sampling period increase from day 1 to day 7, but due to the lack of replication and relatively high measurement error, these values are not significant.

### 5.7: Wet Bulk Density

There are several difficulties with sampling for bulk density and comparing the results. Windrow bulk density can have large inherent variation. Too few samples can lead to results that reflect this variability rather than the underlying bulk densities. Taking too many samples can affect the transport processes in the windrow.

Direct comparison of bulk densities is hampered because successive samples are rarely taken from exactly the same depths. Therefore, even if the variation of bulk density with depth is the same, differences in sampling depth lead to apparently different bulk densities for locations that are nominally the same. The data are best compared when used in conjunction with a model of bulk density. This has not been done, so the comparisons are somewhat crude.

Initial experimentation to evaluate the method used to sample for bulk density indicated that the coefficient of variation is approximately 11 percent (See Chapter 4).

Figure 5.38 presents bulk densities by location for Windrow 1. Similar data from Windrow 2 are shown in Figure 5.39. The availability of data on the position of each sampling location in the windrow is given in Appendix H. The average bulk density by location in each windrow turning is shown in Figure 5.40.

Comparison of the bulk densities for Windrow 1B with the overall bulk density calculated from the weight of the windrow and its measured dimensions provides another check on the bulk density sampling method. The gross bulk density of 442 kg/m<sup>3</sup> compares favorably with the bulk densities shown in Figure 5.38. Even though the gross bulk density is greater than the bulk density at most locations, this is not a problem. The bulk density sampling method is not able to sample deep in the interior of the windrow where the greatest bulk densities are located.

Experimental wet bulk densities range from 150 to 250  $Kg/m^3$  near the surface to 300 to 650  $Kg/m^3$  in the center of the windrow. Windrow bulk density shows the expected trend of increasing with windrow depth. Only 5 of the 82 sampling pairs (6 %) do not show this trend. Location 6 exhibited the greatest incidence of decreasing bulk density with depth with 3 of the 5 sampling pairs.

Changes in density with respect to time are inconsistent. Figure 5.41 presents information on whether bulk density at each location increases from the beginning to the end of a windrow turning. With one exception,

		200	510		861	324	368		246	222	314	
ay 7		266 304	346		178	262	399			279	294	
Ã		219	310			204	307			245	287	tion
		166	272			232	343				189	locat
												3) by
		153	485		157	257	969		202	262	631	(kg/m
ay 3	1A	219 261	442	8	164	290	428	1C	209	390	298	nsity 1.
Å	<u> Vindrov</u>	311	345	Windrov		189	288	Windrov		226	344	lk der ndrow
		170	244			226	330				214	Wet bu for Wi
												38:
		183 282	509		189	334	114		171	310	588	re J
ay 1		192 278	539		168	321	585		233	330	369	Figu
Δ		193	253			171	273			172	307	
			204			143	290				238	

		236 287	398		214	316	371		153	53	577	
ay 7		190 292	406		220	301			190	557	484	
ä		303	264			236	364			234	398	ion
			256				215				237	locat
												βų
		258 272	439		184	224	490		210	313	485	(kg/m <sup>3</sup> )
ıy 3	2A	164 433	450	28	198	278	408	2C	241	341	487	sity
Da	Vindrov	254	222	Nindrov		247	320	Kindrov			385	.k den
							220				293	Wet bu]
												39: 1
		216 297	343		186	275	528		180	387	369	re 5.
ay 1		175 289	458		165	299	464		168	328	155	Fiqu
ä		239	293			223	260			243	299	
			200				223				230	

for Windrow 2.

	Windr	ov 1A			Wind	ov 2A	
		226	179			176	237
168	241	281	286		265	338	285
240	303	442	501	228	260	438	393
	Windr	ov 18			Windr	ov 2B	
		170	181			194	195
200	224	291	305		235	293	272
321	187	471	514	219	315	436	462
	Windr	ov 1C			Windr	ov 2C	
		147	206			200	181
	214	333	276		239	409	310
214	313	320	511	253	361	375	477

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Figure 5.40: Average wet bulk density (kg/m<sup>3</sup>) by location and turning for Windrows 1 and 2.

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approximately 68 % (s = 6.5 %) of the locations experienced increases in bulk density over time. Locations 6 and 9 (Figure 5.42) have the lowest incidence of bulk density increases over time with only 17 % (1 of 6) turnings showing increases.

When the effect of the 11 % coeffient of variation encountered in preliminary experiments is considered, the effect of time on windrow bulk density becomes even less conclusive. When this criterion is applied, decreases over time greater than 11 % were present as much as 56 % in some cases and were seen in all windrow turnings. 37 percent of the locations in each turning show changes in wet bulk density less than ± 11 % of the coefficient of variation. Increases in wet bulk density greater than 11 % occur at 36 percent of the locations while decreases in wet bulk densities greater than 11 % of initial values occur at 27 percent of the locations. Figure 5.43 summarizes these results.

Until the core sampling method can be better calibrated, densities should be considered accurate in a relative as opposed to an absolute sense. Bulk density does appear to change with depth, but the effect of the process on bulk density changes with time was not clear with the method used in this study.

# 5.8: Porosity

Porosity at each sampling location is calculated using the results of the bulk density and volatile solids





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 Locations

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Figure 5.43: Wet bulk density changes over time greater than 11 % coefficent of variation.

calculations according to the method described in Chapter 4. The porosity measurement is therefore subject to all of the uncertainties described in the bulk density and volatile solids section. In addition, the method does not distinguish between porosity within the compost particles and that between the compost particles.

Porosities for Windrows 1 and 2 are given in Figures 5.44 and 5.45, respectively. Average porosities for each turning are shown in Figure 5.46.

Porosities vary from 0.98 to 0.97 at the surface of the windrow, to 0.95 to 0.92 in the windrow interior. As expected, porosity generally decreases with depth. The accuracy of the porosities cannot be evaluated until a bulk density model is developed. The effect of time on porosity

7 Yed	0.966 0.972 0.959 0.961	0.951 0.929		0.974 0.971	0.962 0.951	0.942 0.947		0.963	0.960 0.962 0.958 0.955
•	0.972	0.959			0.971	0.956			0.964 0.958
	110.0	0.965			0.968	0.955			0.972
	0.980 0.958 0.958	0.937		0.978	0.962	0.903		0.970	0.961 0.911
	0.973 0.968	0.942	18	0.976	0.957	0.937	10	0.969	0.945
Vindrov	0.959	0.957	Windrow		0.973	0.959	Ni ndr ov		0.950 0.950
	0.977	0.969			0.966	0.953			0.968
	0.976   0.964	0.934		0.974	0.956	0.935		0.975	0.957 0.917
7	0.976 0.965	0.931		0.977	0.957	0.921		0.966	0.955 0.949
	0.975	0.967			0.975	0.963			0.976 0.957
		0.974			0.980	0.961			0.966

Figure 5.44: Porosity by location for Windrow 1.

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		0.969 0.957 0.942		0.971 0.955 0.948	]	0.979	0.920
/ Kea		0.977 0.964 0.945		0.972 0.958		0.975 0.975	0.934
-		0.964 0.965		0.966 0.948		0 0CD	0.946
		0,968		0.970			0.967
		0. 967 0. 962 0. 937		0.973 0.981 0.935		0.971	0.936
2 A	2 <b>A</b>	0.982 0.952 0.937	2 <b>B</b>	0.973 0.960 0.945	20	0.968 ^ 968	0.935
5	Nindrov	0.971	Nindrov	0.966 0.955	Nindrov		0.947
				0.972			0.960
					_		
		0.975 0.961 0.952		0.975 0.962 0.930		0.976	0.952
		0.980 0.962 0.945		0.978 0.959 0.937		0.978	0.941
-		0.972 0.963		0.971 0.966		770 V	0.959
		.977		0.970			0.969

Figure 5.45: Porosity by location for Windrow 2.
Windrov 1A				Wind	irov 2A		
		0.972	0.975			<b>0.</b> 980	0.970
0.977	0.969	0.964	0.961		0.969	0.959	0.960
0.969	0.961	0.941	0.933	0.973	0.967	0.942	0.944
	Wind	irov 18			Wind	irov 28	
		0.976	0.974			0.974	0.973
0.971	0.973	0.959	0.956		0.968	0.959	0.966
0.956	0.959	0.933	0.928	0.971	0.955	0.941	0.938
	Wind	rov IC			Wind	rov 2C	
		0.645	0.969			0.974	0.975
	0.969	0.953	0.960		0.967	0.944	0.958
0.969	0.955	0.955	0.928	0.965	0.951	0.937	0.936

Figure 5.46: Average porosity by location and turning for Windrows 1 and 2.

is similar to that for bulk density. Five of the six turnings had an average of 70 percent of their locations showing decreases over the 7 day compost turning period. Figure 5.47 presents this information. Porosity changes over time by location are shown in Figure 5.48.

## 5.9: Free Air Space

Free air space calculations are made using the results of the wet bulk density, moisture content and volatile solids content for each location as discussed in Chapter 4. Figures 5.49 and 5.50 give the free air space for each location in Windrows 1 and 2, respectively. Figure 5.51 presents the average free air space values by location for each windrow turning.

Free air spaces of 0.87 to 0.71 are found near the





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	7	ß	
83	9		
100 83	50 6	20	
100 83	83 50 6	67 20	

Figure 5.48: Porosity changes over time by location.

		0.815 0.751 0.528		0.818	0.661		0.775	0.711
Day 7		0.753 0.718 0.680		0.836 0.758	0.633		0.744	0.730
		0.796 0.711		0.812	0.717		0.775	0.736
		0.847 0.748		0.786	0.682			0.827
		0.858 0.716 0.549		0.855 0.764	0.357		0.814	0.418
ay 3	VI	0.796 0.757 0.590	8	0.849 0.734	0.606	10	0.808 0.641	0.726
<b>A</b>	Windrov	0.711 0.678	Windrov	0.826	0.734	<u> </u>	0.792	0.683
		0.842		0.792	0.696			0.804
		0.830 0.737 0.527		0.826 0.691	0.559		0.843	0.458
l 1		0.821 0.741 0.498		0.845 0.703	0.458		0.786 0.696	0.659
Ð		0.820 0.765		0.836	0.747		0.841	0.717
		0.810		0.868	0.732			0.781

Figure 5.49: Free air space by location for Windrow l.

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	0.785 0.741 0.639		0.804 0.712 0.661		0.861 0.791 0.474
Day 7	0.824 0.731 0.629		0.798 0.727		0.827 0.493 0.558
	0.719 0.757		0.784 0.669		0.787 0.637
	0.765		0.803		0.784
	0.764 0.752 0.602		0.833 0.788 0.551		0.808 0.714 0.556
24	0.847 0.597 0.589	28	0.820 0.747 0.626	x	0.780 0.688 0.554
Vindrov	0.763 0.794	Nindrov	0.774 0.707	Vindrov	0.648
			0.797		0.733
	88		S 8 12		22 65
	0.79 0.72 0.68		0.82 0.74 0.51		0.83 0.64 0.66
	0.837 0.735 0.575		0.848 0.727 0.575		0.846 0.700 0.601
-	0.779 0.730		0.796 0.761		0.779 0.726
	0.815		967.0		0.790

Figure 5.50: Free air space by location for windrow 2.

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	Wind	irov 1A			Win	drov 2A	
		0.790	0.834			0.836	0.782
0.845	0.776	0.739	0.735		0.754	0.688	0.740
0.777	0.718	0.589	0.535	0.527	0.760	0.598	0.643
	Wind	irov 18			Wind	Irov 2B	
		0.843	0.833			0.822	0.822
0.815	0.825	0.732	0.719		0.785	0.734	0.749
0.703	0.733	0.566	0.526	0.799	0.712	0.601	0.576
	Wind	rov 1C			Wind	rov 2C	
		0.531	0.811			0.818	0.835
	0.803	0.694	0.746		0.783	0.627	0.717
0.804	0.712	0.705	0.529	0.769	0.670	0.571	0.564

Figure 5.51: Average free air space by location and turning for Windrows 1 and 2.

windrow surface. In the interior of the windrow, free air space ranges from 0.36 to 0.69. Free air space decreases with depth. No changes over time were observed (Figures 5.52 and 5.53).

The coefficient of variation of the free air space measurements from the preliminary experiment is 7.5 %. Applying this  $\pm$  7.5 % factor to free air space changes over time led to the result that for 69 percent of the locations, free air space does not show a change greater than  $\pm$  7.5 %, with 16 % showing an increase and 15 % showing a decrease in free air space for the 1 week compost turning period (Figure 5.54).





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Figure 5.54: Free air space changes over time greater than 7 % coefficent of variation.

# 5.10: Additional Moisture and Physical Properties

Volumetric moisture content ( $\theta$ ), volumetric solids content ( $f_s$ ), void ratio ( $\epsilon$ ), and the degree of saturation (s) were calculated according to the methods described in Chapter 4. The results are presented in Figures 5.55 to 5.62. The implications of these results are discussed in Chapter 6.

# 5.11: Windrow Color Changes

When the windrows were pulled apart, three separate color zones could be seen. Profiles of the front half of Windrow 1 cross-sections are shown in Figure 5.63. Figure 5.64 shows cross-sections of the left and right side of the fron half of Windrow 2. The method of note-taking for these observations was not standardized until Windrow 2 was

	0.158 0.211 0.402		0.153 0.249 0.286		0.188 0.196 0.244
lay 7	0.213 0.240 0.271		0.138 0.204 0.308		0.216 0.228
_	0.175 0.248		0.160 0.240		0.188 0.222
	0.131 0.217		0.182 0.272		0.146
	0.122 0.242 0.388		0.123 0.198 0.546		0.156 0.202 0.493
ay 3 1A	0.177 0.211 0.352	81	0.127 0.223 0.331	10	0.161 0.304 0.231
D Vindrov	0.248 0.279	Nindrov	0.146 0.225	Ni ndr ov	0.176 0.267
	0.135 0.196		0.174 0.257		0. 164
	0.146 0.227 0.407		0.149 0.265 0.376		0.136 0.254 0.459
ay 1	0.154 0.224 0.433		0.132 0.259 0.463		0.181 0.259 0.289
Ω	0.155 0.202		0.139 0.215		0.134 0.239
	0.165		0.112 0.229		0.185

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Figure 5.55: Volumetric moisture content by location for Windrow l.

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	0.185 0.216 0.303		0.167 0.243 0.287		0.119 0.176 0.446
Jay 7	0.154 0.233 0.316		0.174 0.231		0.149 0.427 0.376
_	0.245 0.208		0.279		0.182 0.308
	0.203		0.167		0.183
	0.203 0.210 0.335		0.140 0.193 0.383		0.163 0.245 0.380
ay 3 2A	0.136 0.355 0.349	28	0.153 0.213 0.318	5C	0.188 0.266 0.381
D Vindrov	0.208 0.180	Ni ndr ov	0.192 0.248	<b>Windrov</b>	0.299
			0.174		0.227
	0.177 0.234 0.264		0.146 0.214 0.415		0.141 0.302 0.290
l y l	0.143 0.227 0.370		0.129 0.232 0.362		0.132 0.255 0.120
ы	0.193		0.175 0.204		0.187 0.233
	0.162		0.174		0.179

Figure 5.56: Volumetric moisture content by location for Windrow 2.

	0.158 0.211 0.071		0.029 0.049 0.053		0.037	0.045
Day 7	0.034 0.041 0.049		0.026 0.038 0.058		0.040	0.042
-	0.028 0.041		0.029 0.044		0.036	0.042
	0.023 0.035		0.032 0.045			0.028
	0.020   0.042   0.063		0.022 0.038 0.097		0.030	0.089
ay 3	0.027 0.032 0.058	8	0.024 0.043 0.063	10	0.031	0.043
D	0.041 0.043	Nindrov	0.027 0.041	Nindrou	0.032	0.050
	0.023 0.031		0.034			0, 032
	0.024 0.036 0.066		0.026 0.044 0.065		0.025	0.083
ay 1	0.024 0.035 0.069		0.023 0.043 0.079		0.034	0.051
a	0.025 0.033		0.025		0.024	0.043
	0.026		0.020 0.039			0.034

Figure 5.57: Fractional Solids content by location for Windrow 1.

	0.031 0.043 0.058		0.029 0.045 0.052		0.021 0.031 0.080	
Day 7	0.023 0.036 0.055		0.028 0.042		0.076 0.427 0.066	
	0.036 0.035		0.104		0.032 0.054	
	0.032		0.030		0.033	tent by 2.
	133 138 153		19		23 42 64	ds cont ndrow
	0000		0.0		000	Soli r Wi
Day 3 V 2A	0.018 0.048 0.063	V 28	0.027 0.040 0.055	v 2C	0.032 0.046 0.065	nal n fo
Nindro	0.029 0.026	Nindre	0.034 0.045	Nindro	0.053	actic catic
			0.028		0.040	.58: Fr lc
	0.025 0.039 0.048		0.025 0.038 0.070		0.024 0.052 0.048	'igure 5.
Day I	0.020 0.038 0.055		0.022 0.041 0.063		0.022 0.045 0.021	LZ4
-	0.028		0.029 0.034		0.034 0.041	
	0.023		0.030		0.031	

		lay 1			-	lay 3				lay 7	
					Windrov	, 1A					
		40.3	41.0			35.5	49.5			28.2	35.3
	39.4	27.9	26.9	41.9	23.5	29.8	22.8	43.0	34.3	23.4	24.8
8.1	29.2	13.5	1.1	31.2	22.3	16.1	15.0	27.5	23.4	19.6	13.2
					<u> </u>	4 18					
		42.0	37.8			40.5	44.2			38.0	33.4
1.1	39.6	22.0	21.5	41.9	23.5	22.4	25.2	29.9	33.9	25.3	19.6
24.6	25.9	11.7	14.4	31.2	23.3	14.8	9.4	21.0	21.9	16.1	18.0
					Windrov	10					
	C 07	28.8	39.4		- VC	31.6	32.5		1 20	0.40	26.2
28.5	22.0	18.6	11.0	30.4	19.2	22.4	10.2	35.3	22.9	22.8	21.2

	31.5 22.4 16.2	33.7 21.2 18.2	47.6 31.4 11.5	
Jay 7	42.9 26.4 17.1	35.2 22.6	39.3 12.2 14.2	
	26.8 27.6	9.6 18.3	30.7	W 2.
	30.3	32.9	23.6	Windro
				for
	28.9 25.0 14.9	26.3 50.9 14.3	33.8 23.0 14.6	ation
ay 3 2A	55.2 19.8 14.9	28 35.7 23.7 17.1	2C 29.8 28.7 14.3	y loc
D Vindrov	37.5	Windrov 28.6 21.5	Windrov 17.9 17.9	tio b
	34.0	34.4	24.0	Void ra
	·			.0
	38.9 24.6 19.7	39.0 25.5 13.2	40.5 18.3 19.7	e 5.6
lay 1	48.1 25.5 17.3	44.3 23.4 14.8	43.7 31.4 46.8	Figur
	<b>34.3</b> 26.3	33.1 28.1	28.6 23.5	
	42.5	32.4	30.9	

	0.162 0.219 0.432		0.158 0.262	200.0	0.195 0.204	
Day 7	0.220 0.251 0.285		0.142 0.212 0.327	<b>0.</b> 36/	0.235 0.235	
	0.180 0.258		0.164	167.0	0.196	for
	0.134		0.180	687.0	0 150	cation
						by loc
	0.125 0.252 0.414		0.126 0.206		0.161 0.210	tion
Day 3 v IA	0.182 0.218 0.374	8	0.130 0.233 0.233	v. 10	0.166 0.322 0.322	atura
Hindron	0.259	<u>Nindro</u>	0.151	V. 233 Windro	0.182	ofs
	0.138 0.202		0.180	0/7.0	011 0	Degree
						61:
	0.150 0.236 0.436		0.153	701.0	0.136	re 5.
lay 1	0.158 0.232 0.466		0.135 0.266 0.502	200.0	0.187 0.275	Figu
1	0.159 0.209		0.143	£77 · 0	0.138	
	0.169		0.115	667.0	191	

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7 Windrow 1.

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Day 7	0.157 0.191 .254 0.242 0.226 0.215 0.335 0.322		0.179 0.172 0.241 0.254 0.302		0.152 0.121 0.188 0.462 0.184 0.326 0.403 0.485	for
	0.210 0		0.172 (		0.189	location
Day 3 Windrov 2A	0.210 0.218 0.357		0. 144 0. 197 0. 410		0.168 0.255 0.406	of saturation by w 2.
	0.138 0.373 0.312	Windrov 2B	0.157 0.222 0.337	Windrov 2C	0.194 0.279 0.408	
	0.215 0.185		0.199 0.260		0.316	
			0.179		0.236	Degree Windro
						62:
Day 1	0.181 0.243 0.277		0.149 0.222 0.260		0.144 0.318 0.305	Figure 5.
	0.146 0.236 0.391		0.132 0.242 0.386		0.135 0.267 0.123	
	0.199 0.242		0.180 0.211		0.194 0.243	
	0.166		0.179		0.185	







Windrow 1C



Windrow 1B

Figure 5.63: Windrow 1 cross-section showing color zones.



Windrow 2A









Windrow 2C

Figure 5.64: Windrow 2 cross-section showing color zones.

started, so the profiles do not contain the same information.

At the outside surface and in the toe area, the compost is dark brown color. Temperatures in this zone are moderately hot. A second zone of mixed brown and white colored material is underneath this first zone. This second zone is typically 15 cm thick near the center line of the windrow and 30 cm thick in the toe area. A well-defined color gradient is present in this zone with the white particles increasing towards the center of the windrow. There is a distinct white line at the interface between the second zone and the yellow third zone. High temperatures tend to correlate with the occurrence of the white line interface. The white line is most noticeable in areas where there was a bloom of mushrooms on the windrow surface.

The third zone is the color of the original uncomposted DMS, usually a yellow to yellowish-brown.

The location of the three zones varies between the end of each successive windrow turning. This can be quantified by looking at the change in the percent of the total area represented by each color and by the depth of penetration of the black and white zone into the windrow at the centerline and bottom of the windrow.

Table 5.4 presents the percent cross-sectional area for each windrow turning profile and color zone. With each successive turning, the average Windrow 2 Zone D area

Windrow		Color (% Area)	
	Yellow	Brown and White	Brown
1A	37		63 <sup>a</sup>
1B	46		54
1C	12		88
2A Left	42	40	18
Right	45	28	27
Average	43	35	22
2B Left	33	38	29
Right	39	46	15
Average	36	42	23
2C Left	27	59	15
Right	34	56	10
Average	31	57	12

Table 5.4: Windrow color changes.

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a Could not calculate brown and brown/white areas from notes. Area percentages represent non-yellow areas.

decreases. The percent area in Zone D in Windrow 1 decreases dramatically from Windrow 1A to Windrow 1C. The left and right halves of Windrow 2 are quite different. This is probably due to differences in windrow size and construction. Zone B in Windrow 2 expands inward with the interior edge moving faster than the exterior edge. Examining the penetration depth data presented in Table 5.5, the side and top penetration depths are very different. Top penetration depths stayed the same or increased slightly with time in both windrows. Average side penetration depths for Windrow 2 increased almost linearly with each turning. The top penetration depths are very consistent when compared to side penetration depths. Variances for top penetration depths are 0.33, 0.25 and 0.33 inches for turnings A, B, and C, respectively, while side penetration depth variances are 4.75, 98 and 108 inches. Side penetration is much more sensitive to the conditions encountered in each windrow: ambient temperature and relative humidity, substrate, and windrow size and shape.

Windrow	Penetration Depth	(cm)
	Side	Тор
1A	89	33
1B	76	36
1C	152	41
2A Left	79	36
Right	80	33
Average	80	34.5
2B Left	114	36
Right	69	36
Average	91.5	36
2C Left	107	40.5
Right	107	38
Average	107	39.25

Table 5.5: Windrow penetration depths.

#### CHAPTER 6

#### DISCUSSION

#### 6.1: Experimental Methods

## 6.1.1: Probe Design

Probe design was generally successful. Probe insertion did not cause the windrow to split apart during the one week turning periods. The probes could be inserted and were durable. Some difficulty was encountered with the repair of damaged gas collection lines; this was solved by taping new lines to the outside of the probe. New designs should allow easier probe assembly/disassembly.

### 6.1.2: Temperature

Temperature monitoring equipment had a calculated measurement error of  $\pm 1.5^{\circ}$ C. Measured variations during calibration were much smaller than this on the order of  $\pm 0.07^{\circ}$ C.

In retrospect, the ability of the experiment to test a key assumption could have been improved. Temperature and gas monitoring points were located in the windrow front half center section to allow replicate samples to be taken. This placement did not allow testing the assumption that longitudinal edge effects were negligible. While two of the three windrows with replicate monitoring locations did not

show evidence of longitudinal effects, these effects cannot be ruled out. The longitudinal effects could have been determined if probes had been placed in one quarter of the windrow.

Additional measurements of temperatures at the windrowair and windrow-concrete boundries would have improved the accuracy of temperature contour figures and aided future modeling efforts.

#### 6.1.3: Gas Concentration

Unexpectedly high oxygen concentrations in the windrow interior suggested that leakage of air had occurred during the experimental procedures. The gas sampling probe and withdrawal equipment functioned very well with no influx of air attributable to these components of the gas sampling and analysis system.

The storage system that was initially adopted was able to function adequately over time periods of less than 2 weeks. Covering the septum top with silicon caulk stopped the sample from leaking out due to overpressures inside the storage tube and greatly extended the storage time. If this type of storage system is to be used in the future, longer term experiments should be conducted to determine the exact length of intact storage. The injection of a fluid into the tube while air samples are being withdrawn would also keep internal pressures closer to atmospheric pressure.

The largest error in the gas system occurred when gas was withdrawn from either the sampling probe or from the

storage system. Correction factors based on experimental work (See Appendix D) accounted for most of the differences between the expected and measured values.

Several correction factors were evaluated: low, high, and average influx. The low and high influx corrections were based on the observation of two separate linear segments in the influx vs. calculated sample pressure data. The low influx correction was based on the initial slope which occurred while calculated sample pressures were less than 1.0 atmospheres. The high influx correction was based on the steeper sloped influx vs. calculated internal pressure data. Calculated pressures in this case were less than 1.0 atmosphere. The physical explanation for these two sloped lines is most likely diffusion for the low influx segment and a pressure gradient for the high influx condition.

The average influx approach represents a compromise due to the uncertainty of the actual initial pressure in the sample tube during sample removal. If this pressure were known, more accurate estimates of gas concentrations could be made.

From a parameter estimation and modeling standpoint, the gas concentration data are probably accurate enough to illustrate basic trends and to do initial estimation and modeling work. Additonal data must be collected, however, to justify more rigorous parameter estimation and model validation efforts. Carbon dioxide data are subject to less

error than the oxygen concentrations because the influx mainly caused the addition of oxygen. The use of a gas valve on the sampling syringe would directly reduce influx and should be used in future experiments.

A large quantity of gas samples were analyzed in this experiment. The available analytical method, a gas chromatograph, is quite time consuming. The use of equipment such as an infared CO<sub>2</sub> analyzer and a paramagnetic oxygen analyzer could speed up the analysis process considerably, particularly if it is onsite.

### 6.1.4: Gravimetric Moisture Content

Gravimetric moisture content determinations had acceptable levels of measurement error with ±2 % wb standard deviation. Measurement errors can be reduced with the use of scales accurate to ±0.01 mg. Sample sizes with wet weights between 2.5 and 3.0 grams can further reduced the range of measurement error. Gravimetric moisture content determinations are also very time consuming.

#### 6.1.5: Volatile Solids

Volatile solids determinations made in this experiment were subject to unacceptable measurement errors with an average standard deviation of ±7 percent. Dry sample weights of 0.7 grams coupled with the use of a scale accurate to 0.01 mg could produced standard deviations of approximately 1 percent.

## 6.1.6: Dairy Manure Solids Sampling and Bulk Density

The rotary corer sampling method proved to be an acceptable way to sample compost materials for insitu bulk density, porosity and free air space determinations. Initial experimentation indicated that bulk density replicates taken at the same depth had coefficents of variation of 11 % for several depths. Windrow bulk densities obtained with the corer were in reasonable agreement with the overall windrow bulk density. This agreement could be more readily determined if samples were taken from deeper in the windrow's interior and if a windrow consolidation model was developed. Examination of the source of bulk density measurement variance indicated that the variance in effective radius measurement was the most significant factor. Future study of the core sampling method for composting materials should focus on the effects of corer speed, radius and compost material on bulk density determinations.

# 6.1.7: Porosity and Free Air Space

Examination of the sources of porosity measurement variance indicated that errors in determining the particle density could affect porosity determinations. This was also an important error source in free air space determinations, but radius measurement errors were the largest source in this case.

## 6.1.8: Dairy Manure Solids Placement

Dairy manure solids placement and operator skill were observed to have a large impact on the apparent bulk density of a windrow. Pushing DMS into position, dropping DMS in a large mass (as opposed to "shaking" it out of the skid steer bucket), and leveling the windrow with the bucket all appeared to increase compaction. Although efforts were made to standardize the placement procedure, placement of DMS into the windrow probably had a large and unpredictable effect on bulk density and therefore on the transport properties in the experimental windrows.

## 6.1.9: Windrow Size Measurements

The method of measuring windrow size changes had acceptable accuracy. Measurement errors were due to sag in the lines, problems with determining the windrow surface, and parallax.

### 6.2: Experimental Results

#### 6.2.1: Temperature

The temperatures encountered during both DMS composting runs were lower than those reported for uncontrolled sewage sludge windrows. A number of factors could have influenced this. The large quantity of water, as indicated by high moisture contents, could have absorbed the heat output of the reaction. This type of behavior was observed for decomposing oat straw in an adiabatic calorimeter by Bartholomew and Norman (1953) Conversely, the windrow size might have been small enough so that heat dissipated before

the temperature could increase. Finally, if the reaction rate was low, the heat output would be low and high temperature would not have occurred.

## 6.2.2: Gas Concentration

There are two possible explanations that can account for the gas concentrations observed in this experiment, in particular the higher than expected oxygen concentrations in the windrow interior. The first hypothesis is that the reaction rate is limiting. In this case the flux of oxygen to the reacting sites is large enough so that oxygen is not rate limiting. The second hypothesis is that the reaction is transport limited. Oxygen flux, in this case, is great enough to supply all the oxygen demanded by the reaction. The high oxygen concentrations would be due to experimental error, in particular the influx mentioned earlier.

The reaction limited hypothesis occurs under two different scenarios: (1) high transport rates/medium reaction rates (HTMR, small windrow), and, (2) medium transport rates/low reaction rates (MTLR, relatively nonreactive substrate).

The system studied in this experiment is not a high rate system: oxygen transport is either by diffusion or natural convection, neither of which is a high-rate process. Forced aeration or even enhanced natural convection were not studied in this experiment. Therefore the possibility that the observed high oxygen concentrations are due to HTMR is not realistic. The MTLR scenario is more plausible in light of the previous points. The lack of change in volatile solids levels indicates an unreactive substrate.

There are several arguements against MTLR, however. The first argument is that volatile solids is not a good indicator of substrate consumption. The volatile solids measurement is not very specific: it cannot distinguish between the original substrate, added microbial mass and material that may be organic but cannot be degraded (Finstein, 1986). As is discussed later, the use of an ash solid basis is a better indication of substrate consumption. There is evidence that substrate is being consumed when volatile solids are expressed on an ash basis.

If the possibility exists that the substrate is not limiting, then the low oxygen concentrations in the windrow interior become more troublesome for MTLR. In this case, these low concentrations could be limiting the reaction. In many microbial systems, including composting, the transport of oxygen across the water film is the limiting rate (Finger, 1975; Haug, 1980). While Haug's assertion is based on forced aeration systems that have high air flow velocities, Finger studied diffusion/natural convection systems that are similar to what is studied in this research. Furthermore, Shell's (1955) study of diffusion in windrows also pointed to the limited ability of the effective oxygen diffusion rate to supply oxygen to an actively composting material.

The strongest challenge to the short-term reaction limited hypothesis is that if the interior measured oxygen levels were not rate limiting, why were higher interior temperatures not observed? During temperature measurements for Windrow 1A, Locations 6 and 10 Figures 5.9 and 5.10) have an "S" shaped profile. Locations 5, 8 and 9, on the other hand, have steep increases followed by a leveling off of temperature.

Substrate is initially the same at the all locations; it is not the cause of the different temperature histories. Possible high temperature limitations do not apply at Locations 6 and 10 as both these temperatures are solidly in the mesophilic range. Referring to the moisture content data presented in Figures 5.32 and 5.33, the wet basis gravimetric moisture contents at all locations are approximately the same, so no difference in the effect of moisture on the reaction rate or heat storage is expected. Examination of wet bulk densities (Figure 5.40) and free air space (Figure 5.51) indicate that the rate of transport of gases, whether by diffusion or natural convection, might be lower in the interior locations (6 & 10) than the locations closer towards the surface of the windrow (5, 8, 9).

Given that other measurements do not provide a ready explanation for the shape of the temperature curves, oxygen transport rate limitations might provide an answer. In Figure 5.10, while Locations 8 and 9 are showing large temperature increases, Location 10 does not increase in

temperature. Only when the temperatures at Locations 8 and 9 level off does the Location 10 temperature increase. The increasing temperatures at the two higher locations increase the reaction rates and most of the available oxygen is consumed, leaving little to diffuse down to Location 10. As reactions at Locations 8 and 9 leveled off due to temperature inhibition, more oxygen diffused down towards Location 10. Oxygen ceased to become a limiting factor in the reaction at Location 10 and the increased reaction began to put out more heat, causing temperatures to increase.

The course of the reaction at Locations 5 and 6 (Figure 5.9) is somewhat different. Temperatures begin to increase before the maximum temperature plateau is reached at Location 5. This could be due to a higher transport rate near the edge of the windrow (Location 6) as opposed to the windrow interior (Location 10). Evidence for this possibility will be discussed in a later section.

Another feature of the temperature profiles that could be explained by oxygen limitations is the leveling off of Locations 6 and 10 before the higher temperatures of 5, 8 and 9 are reached. In this case, while the reaction rate at the higher temperatures is reduced, it is still occurring and consuming oxygen. Therefore, while more oxygen is being transported into the windrow interior, not enough is present in the free air space at Location 10 to permit a reaction that is not limited by low oxygen concentrations. If higher oxygen transport rates were present at Location 6, the

oxygen concentration might be higher than that at Location 10, although still rate limiting. The higher temperatures would be due to a higher rate of reaction caused by oxygen concentrations which are less limited in the free air space.

A potential objection to the temperature level argument for oxygen transport limitations that heat conduction from the bottom of the windrow was enough to limit the temperature rise. This could indeed be an explanation, particularly if the ground was very cold, because of the large thermal mass of the earth.

Measured slab temperatures during this period are very close to those at Location 10 and increase along with that temperature. In addition, one would expect this problem to occur in the winter when the ground was very cold. Both tests were conducted in the summer and fall, however, presumably after the ground had warmed up. Furthermore, DMS had been composted there for several months previously, so heat stored in the ground would have limited this effect.

Based on the evidence presented above, I feel that a oxygen transport limitation is the most probable explanation for the gas concentration data.

A common assumption in forced air composting is that the sum of measured oxygen and carbon dioxide concentrations equal 21 percent. This is roughly the concentration of oxygen in the ambient environment. The sum of oxygen and carbon dioxide at several locations in the compost windrows I studied was greater than 21 %, however. Initially, I

thought that I had encountered another indication of experimental error. Re-examination of the mushroom composting literature revealed that carbon dioxide concentrations could become as high as 30 % in windrow interiors (Lambert and Davis, 1934). The high carbon dioxide concentration in Lambert and Davis' study was correlated with zones of "green" manure and they suggest that manure decomposition is retarded in this area.

## 6.2.3: Volatile Solids

Volatile solids measurements had several problems associated with their use. The method chosen to measure volatile solids was subject to large measurement errors. Future work that uses volatile solids will need to use more accurate techniques, as described in Section 6.1.5, above.

Expression of volatile solids on an ash solids basis is more sensitive to changes in volatile material than expression of volatile solids on a dry solid basis. Expressed as a percent decrease in the original ash fraction, the dry solids basis decreased only 8 %, while the ash solids basis decreased between 30 and 44 percent.

The conversion to measuring substrate and substrate consumption on an ash solids basis correlates more closely with other indications that a composting reaction was occurring. The large changes in temperature, gas concentration and compost color can therefore be supported by evidence of substrate consumption.

While the volatile solids determinations do provide a

rough measurement of biological activity, its usefulness is limited because it lacks both specificity and sensitivity. Finstein et al. (1986) note:

The test fails to discriminate among readily metabolized, putrescible material, less readily metabolized material, and organic material that is not metabolized during any reasonable composting period. Process performance is primarily concerned with the first of these, secondarily with the second, and not at all with the third. Also,...both fresh organic waste and stabilized organic residue are included in the VS test, which decreases sensitivity.

Similarly, sensitivity is poor because a high percentage of the dry weight is volatile matter. This means that the decomposition of a large amount of VS may result in only a small change in percent VS.

In the last 10 years most of the theoretically sound work with composting has been done with sewage sludge and garbage (Haug, 1980; Finstein and Morris, 1975). Volatile solids has been used successfully as an indicator of substrate consumption (Higgins et al, 1982) in those reactive substrates. I based my work closely on this experience. I neglected to consider the relatively inert nature of the DMS substrate, however, and volatile solids expressed on a dry basis showed little change. The mushroom composting industry deals with straw based substrates that are very similar to DMS. They express volatile solids consumption on an ash basis in their work (Burrows, 1951). It would appear that in dairy manure solids composting, volatile solids should also be expressed on an ash basis.

Even though the use of the ash solids fraction allows substrate level changes to be observed, for detailed work more specific measurements of the substrate are useful. The adoption of the procedures used in the mushroom composting industry as described by Mueller (1962) present an alternative. He recommended analyzing cellulose, lignin, pentosans (90 % of hemicellulose), ether and hot water extracts, and soluble and insoluble ash contents. Determination of the total carbon, total nitrate and ammonia nitrogen and nitrogen in lignin and alpha cellulose is also important for research work.

### 6.2.4: Moisture Content

Moisture content changes expressed as a percent wet basis do not exhibit major changes in either of the two windrows: 81 to 77 % in Windrow 1 and 80 to 77 % in Windrow 2. This observation can be misleading, however. The wet basis expression can mask changes in the moisture content that are significant.

Both windrows had final moisture contents of approximately 77 % wb. Initially Windrows 1 and 2 had 81 and 80 % wb, respectively. The corresponding percent dry basis values are 335, 426 and 400 % db. A 21 % decrease in the intial weight of water of Windrow 1 was observed; Windrow 2 had a 16 % decrease from the initial weight of water.

Another advantage of the dry basis expression is that at the lower moisture contents it relates more directly to changes in the drying rate. Bohnhoff and Converse (1986) found that the point where the DMS drying rate changed from

a constant rate to a falling rate was at approximately 30 % db. This corresponds to 23 % wb.

While the expression of gravimetric moisture contents on a dry basis is more sensitive to changes in water weight, the denominator is affected by the change in solids weight due to composting. Therefore it should also be corrected to an ash solids basis, although this will result in very large percentages.

In addition to the problems mentioned with the wet basis moisture content, considering moisture contents on a gravimetric basis hides changes in water relationships that affect compost windrow heat and mass transfer.

#### 6.2.5: Bulk Density

Wet bulk density changed with depth but did not show a change over time. The change with depth is not suprising. In-situ measurments of bulk density at specific points in compost windrows have not been previously reported in the literature, however. Disturbed sample bulk density and gross bulk density have been measured but given the variation with depth found in this experiment, they do not adequately describe the local conditions inside the windrow. Given the importance that bulk density plays in a variety of heat and mass transfer parameters, accurate bulk densities are crucial if distributed parameter heat and mass transfer modeling is to be conducted.

Bulk density appeared to be relatively constant over time because of the relative lack of precision in the method
of measurement. The coefficent of variation of approximately 11 percent lead to the uncertainty of the bulk density determination of  $\pm 17 \text{ kg/m}^3$  for lower bulk densities and  $\pm 51 \text{ kg/m}^3$  for the largest bulk densities encountered. If longer term or high rate systems are to be studied, windrow consolidation and bulk density increases will need to be measured. Therefore, an improvement in the core sampling method to improve its accuracy and precision is imperative.

# 6.2.6: Additional Derived Physical Parameters

A wide range of physical parameters are derived from the moisture content, volatile solids and wet bulk density measurements.

The porosities encountered in this experiment are rather high, typically above 90 percent. This indicates that the pore spaces in this material occupy a high proportion of the total volume. Given that the compost substrate is a fibrous material with a high internal porosity and that the particle density of the DMS is fairly high, this is not too suprising.

The volume of water also has important implications. This can be expressed in several fashions: free air space, volumetric moisture content and degree of saturation. When compared with the wet basis moisture contents that were fairly constant, all three of these parameters show that on a volume basis, water content increases with depth.

The free air space measurement indicates that as depth

increases, there is less space occupied by voids where gases can be transported through. This can significantly reduce the transport of oxygen either through the void spaces or across the thicker liquid films that are present at greater depths. Experiments by Shell (1955) on diffusion of oxygen through a composting mass support this observation.

The volumeteric moisture content ( $\Theta$ ) can affect thermal conductivity. Increasing the volume of water in the seriesparallel models of thermal conductivity will increase k as water displaces air. Bohnhoff et al. (1983) observed just such a relationship between k and  $\Theta$ .  $\Theta$  is also more convenient to use when calculating fluxes of water through the composting mass.

In comparison with other composting systems, the dairy manure solids system composts at very high moisture contents between 76 and 81 % wet basis. The  $\theta$  and high f<sub>a</sub> values point towards an explanation as to why composting could take place. Free air space values measured in the DMS windrow did not even approach the free air space limitations observed in other substrates at FAS values below 30 percent. This is probably due to the relative structural stability of the dairy manure solid particles that were able to form a porous windrow and the high moisture content of the particles themselves.

The degree of saturation is useful in predicting the effective stress on a material when bouyancy forces are considered. Both the degree of saturation and the void

ratio are preferred expressions in soil mechanics where prediction of compaction and consolidation are important.

Many of the properties discussed in this section are derived directly from the soil mechanics and soil physics literature. While they provide insight into the physical processes in composting, a significant difference exists. Unlike most soil materials, compost particles are compressible. This means that under enough pressure, the internal porosity of a compost particle can be reduced. Therefore the nature and size distibution of pores may change significantly at greater depths. Intra-particle water may be expressed into inter-particle pore spaces. Particles that have been crushed during one windrow will respond differently to stress when redistributed and reloaded. Models of windrow bulk density must deal both with the effects of compressibility and changes in compressibility over time.

### 6.2.7: Thermal Properties

An important simplifying assumption made by Finger (1975) was that thermal and physical properties in a compost windrow were neither spatially or temporally variable. From the results of this investigation, it appears that some of the physical properties do vary spatially. The question remains whether this physical property variance affects heat transfer properties.

In order to evaluate the potential thermal property spatial variability, I calculated a number of thermal

properties using temperature, moisture content and bulk densities at 9 locations in Windrow 1B on days 1, 3, and 7. Empirical equations by Bohnhoff et al. (1984) for thermal conductivity, specific heat and thermal diffusivity were used. The results of the calculations are shown in Table 6.1.

Specific heat variability is very small in this windrow. The maximum difference between the largest and smallest values at any time is 2 percent. Thermal diffusivities exhibit greater spatial variability. Comparison of locations at any time reveals differences of 16 to 30 percent.

Spatial variability in thermal conductivity is very large. The maximum percent difference ranges from 150 % to 320 percent. There is a pattern to this variability as well: the outer surface and windrow interior have low and high thermal conductivities, respectively. The low exterior thermal conductivities provide insight into why the interior the windrow tends to heat up. It would appear that the assumption of constant thermal and physical properties is not accurate.

# 6.2.8: Windrow Size Changes

There was evidence of windrow size changes both during the windrow composting periods and between different periods. Typically, during a one week composting period, the center of the windrow would have the greatest decrease and the windrow toe would show a slight increase. The

		Day 1				Day 3				Day 7	
		50.8	50.8			49.7	52.4			42.8	51.2
	57.5	53.9	53.4		62.7	64.9	58.5		55.7	68.1	61.4
59.4	53.3	45.7	44.9	65.1	61.5	51.0	48.7	46.0	57.7	60.1	55.6
				Temperat	aure, C	(5 =	+/-1.5 C	)			
		78.6	78.8			77.3	78.3			77.8	77.3
	78.5	78.8	79.4		77.6	77.2	77.4		78.2	77.4	77.1
79.2	79.0	79.1	78.8	78.0	77.7	77.3	78.5	79.5	78.0	77.4	77.8
			Moi	sture Con	itent, 7	lvb (s	= +/-2.2	Zvb)			
		168	189			164	157			178	198
	177	321	334		189	290	257		204	262	324
230	273	585	477	330	288	428	696	343	307	399	368
			B	ulk Densi	ty, kg/	' <b>a^</b> 3 (s	; = +/-11	1)			
		0.132	0.149			0.127	0,123			0.138	. 153
	0.139	0.259	0.265		0.146	0.223	0.198		0.160	0.204	0.249
0.229	0.215	0.463	0.376	0.257	0.225	0.331	0.546	0.272	0.240	0.308	0.286
				Volumet	ric Moi	sture C	Content				
		0.074	0.082			0.071	0.072			0.070	0 084
	0.083	0.140	0.142		0.092	0.137	0.114		0.092	0.130	0.146
0.132	0.116	0.239	0.186	0.157	0.133	0.174	0.301	0.134	0.136	0.178	0.157
				Thermal	Conduc	tivity,	W/m^2 C				
		3.51	3,52			3.47	3.50		•	3.48	3.47
	3.51	3.52	3.54		3.4B	3.46	3.47		3.50	3.47	3.46
3.53	3.52	3.53	3.52	3.49	3.48	3.47	3.51	3.54	3.49	3.47	3.48
				Spe	cific H	leat, Kj	i/kg C				
		1.26	1.23			1.25	1.30			1.12	1.22
	1.34	1.26 1.24	1.23		1.40	1.25	1.30 1.28		1.29	1.12	1.22

Table 6.1: Effect of windrow physical property variability on the calculated thermal properties in Windrow 1B.

largest changes in the center of the windrow occurred from day 1 to day 3. The experimental design did not include detailed size measurements immediately after windrow o construction. If this had been included in the design, large changes might have been observed.

The small changes in windrow size are not suprising due to the shortness of the experiment and the type of composting system studied. Other researchers that have noticed larger changes either monitored long term changes in windrow systems (Mears et al. 1975), or studied higher rate systems (i.e. forced aeration) (Steniford et al., 1984).

The difference between the small changes that I observed in the experimental DMS windrows and those reported by Steniford et al. (1984) in co-composted forced aeration systems may indicate that high rate composting leads to changes in particle size that affect consolidation behavior. Chang and Rible's (1972) analysis of the particle size distribution and the nutrient content of fresh and composted dairy manure indicates that composting decreases the proportion of small particles in the overall particle size distribution. If longer term composting systems are to be studied, the effect of composting on particle size and windrow consolidation should be examined.

# 6.3: Reaction and Transport Characteristics

### 6.3.1: Type of Reaction

The oxygen concentration profiles presented in Figure 5.26 and 5.27 provide insight into the type of reaction that

is occurring. By analogy with the diffusion of a gas into a reactive spherical particle, when the rate of gas diffusion is less than the reaction rate, the gas concentration profile falls very quickly from the ambient level near the particle surface to very low levels that are maintained in most of the particle (Findlayson, 1980). This description is almost identical to the oxygen concentration profile mentioned earlier.

In such cases, the Thiele modulus, or dimensionless ratio of the characteristic time for transport to the characteristic time of reaction, is much greater than 1. This occurs with a fast reaction and relatively slow transport of oxygen and heat (Findlayson, 1980). The exact value of the Thiele modulus is hard to determine because of the non-isothermal composting reaction. Difficulties that I encountered with the gas sampling and analysis system prevented accurate determination of this modulus.

The active presence of fungal masses in the advancing color zone, the deeper penetration of the color zone with each windrow turning, and the relatively poor nutrient status of flushed and separated dairy manure solids suggests that substrate limitations were present and may have caused the classic microbial population progression to be short circuited to the fungal recolonization period.

### 6.3.2: Unreacted Core Model

The overall course of the composting reaction behaved like an unreacted core model of a reactant being transported

into a reactive mass (Levenspiel, 1972). According to the unreacted-core model, the reaction proceeds at a narrow front which moves into the solid particle. The substrate is completely consumed as the front moves through the particle, leaving behind an unreactive mass.

As applied to the composting windrow, the windrow itself would correspond to the particle. Evidence of a moving reaction front is provided by the observed movement of the temperature, oxygen, carbon dioxide and color profiles through the windrow over the course of the composting period.

The rate at which each of the observed fronts moves through the windrow can also be accounted for with the unreacted core model. Initially, the reaction consumes the oxygen very rapidly. The controlling step quickly becomes the oxygen transport rate, and zones with low oxygen concentrations have lower or non-existant aerobic reactions.

In those areas where aerobic reactions are occurring, the rate of heat transfer begins to affect the reaction. In areas with low heat transfer, the temperature builds up and reactions increase. This process continues until inhibitory temperatures are reached and the reaction rate decreases. With this rate decrease, less oxygen is consumed and more is available for transport to locations deeper in the windrow.

Finally, as the reaction proceeds, substrate at the initial location is consumed to where it cannot support high rate reactions. The front between the "consumed" and fresh

dairy manure solids moves inward.

The observed composting reaction was more complex than the classic unreacted core model. Additional transfer resistances due to transport inside the windrow and across the water film surrounding the DMS compost particles must be included. Another complication is that the composting reaction occurs across a diffuse front rather than a sharp interface between the spent and fresh solid zones. Finally, the presence of temperature gradients influences both reaction and transport.

These complications can be dealt with, however. Levinspiel (1972) describes how the combination of resistances can be handled and what implications the different resistances have for what the controlling rate is. The diffuse front problem is considered by Wen (1968) and Ishida et al. (1971a). Wen and Wang (1970) treat the effect of non-isothermal reactions.

### 6.3.3: Pore Space Heat and Mass Transfer

In the composting literature there is a consensus that heat and mass transfer in the pore spaces of windrow composting systems is primarily due to natural convection. Support for this comes from a variety of sources and includes anecdotal observations of steaming windrows, higher oxygen concentrations over buried tile inlets (Lambert and Davis, 1932), comparison of the maximum observed composting reaction rates to oxygen diffusion rates (Shell, 1955) and simple models of natural convection caused by temperature

and moisture content gradients (Haug, 1980).

While there is no reason to doubt that these inferences are incorrect, there is no direct proof that natural convection as opposed to diffusion is the major heat and mass transfer mechanism. A major reason for this lack of proof is the difficulty in measuring natural convection in uncontrolled environments.

In my observations of the depth of penetration of the color zones in the compost windrow, there is some evidence that two different types of transport were present. Comparison of the depth of penetration of white colored zone at the top and sides of each windrow turning at completion indicated that the side penetration was 2.4 to 3.1 times greater, depending on the length of composting. The depth of penetration of a reactive front over time is a rough indication of the ratio of the rate of transport to the rate of reaction or Thiele modulus.

The observed difference between the top and side of the windrow could be due to different reaction rates or methods of heat and mass transfer. Reaction rates are affected by the substrate, oxygen availability, and temperature. After the DMS is mixed and placed into a windrow, the substrate is assumed to be the same in both locations.

Oxygen concentrations and heat removal are affected by transport. Higher transport rates increase reaction rates by providing more oxygen. Higher heat transport lowers reactions initially but prolongs a reaction by delaying

inhibitory temperatures. The effect of higher transport rates on the Thiele modulus for oxygen is therefore somewhat ambiguous.

If the rate of reaction of the substrate is considered, the effect is not ambiguous, however. Because of the higher oxygen concentrations and lower temperatures due to higher transport rates, the substrate is consumed more quickly. The reaction front moves inward at a more rapid pace where transport rates for oxygen and heat transfer are larger.

This experimental observation provides strong evidence that two different rates of transport processes are present in windrow composting systems. These observations need to be better quantified before they are considered proven. The evidence presented above is also not sufficent to conclude what types of transport are present. Higher free air space in the side could lead to greater rates of diffusion in that area as compared with the top, for instance. Other potential mechanisms include diffusion or roll type convective cells in the top portion and in the windrow side, diffusion, natural convection, or even heat conduction through the slab.

# 6.4: Pathogen Survival

The ultimate concern with studying DMS composting is to determine whether it can produce a bedding material that is sufficiently free of mastitis-causing organisms that it will not cause outbreaks of mastitis when used by dairy cattle. This concern can be addressed by considering the effect of

observed composting conditions on the survival of pathogenic organisms.

Microbial survival and growth is affected by a number of factors including time-temperature conditions, gas concentrations, moisture content, water activity, pH and substrate availability. Time-temperature profiles are the most important factor in composting and will be the subject of the rest of this discussion.

The discussion in the Literature Review indicated that there are a variety of standards for composting timetemperature curves. A common one is the maintenance of 55°C for three days. This criterion is based on refuse composting where there is a concern with micro-organisms that have higher sterilization temperatures than the mastitis-causing organisms. Temperatures from 50°C to 55°C are minimally to moderately inhibitory for E. coli. 35 to 45°C encompasses the optimum growth temperature range for E. coli. Accordingly, these three criteria were applied to the time-temperature data in Tables 5.2 and 5.3. The number of hours spent in each temperature range are presented in Table 6.2. An assessment of the impact of the time spent in each temperature range criteria as presented in Figure 6.1. Looking at Figure 6.1 it is apparent that while there are zones of temperatures lethal to coliforms there are also areas that have sublethal or even optimal temperature for growth. Generally, the toe area and the center of the windrow seem to have the largest potential for E. coli

Windro LOC	W 1A	18	Time (hou 1C	rs) 2A	2B	2C	
Т	> 55 C						
1 2 3 4 5 6 8 9 10	117 144 128 0 125 0 119 93 0	76 151 130 0 136 45 0 133 7	0 0 na 151 114 0 19 95	0 109 33 112 49 0 107 0 0	0 117 155 156 148 117 151 100 0	0 76 83 88 76 24 88 56 0	
Т	> 50 C						
1 2 3 4 5 6 8 9 10	159 155 146 0 142 0 143 126 0	131 158 156 54 150 94 157 157 73	0 24 56 na 158 132 0 135 116	40 127 62 126 80 0 123 8 0	12 161 158 160 162 148 159 128 38	0 99 89 96 84 47 96 72 13	
3	5 < т < 4	15					
1 2 3 4 5 6 8 9 10	0 0 137 14 74 12 21 136	0 0 36 0 0 0 41	71 95 63 0 0 0 164 17 5	21 2 41 2 38 73 2 64 31	123 2 0 2 0 2 0 4 57	73 0 4 0 8 33 0 2 31	

Table 6.2: Length of time spent in selected temperature ranges by location and windrow.



L = T > 55 C for 3 days.

N = T > 50 C for 3 days.

G1 = Optimum regrowth temperatures > 10 hours.

62 = 30 < Optimum regrowth temperatures < 100 hours.

G3 = Optimum regrowth temperatures > 100 hours.

Figure 6.1: Summary of assessment of timetemperature effects on microbial survival and growth. survival and regrowth. Based on the number of locations that had temperatures greater than 50 or 55°C, both windrows seemed to be equally effective. When the length of time that a location had optimal E. coli growth temperatures is considered, Windrow 1 had only half as many survival zones as Windrow 2.

Another way to evaluate the effect of a timetemperature curve on organism survival is to calculate the number of log reductions that it causes. Following the procedure described by Haug (1980), k<sub>d</sub> as a function of temperature was calculated for "coliform bacteria" with time-temperature survival data originally developed by Ward and Brandon (1977). The equation developed was

 $k_{\rm d} = 0.216 \, \exp \left[ 0.145 \, * \, ({\rm T_C}{\rm -50}) \right] \qquad (6.3)$  where  ${\rm T_C}$  is the material temperature in degrees C. Equation 6.3 was substituted into

$$\ln (n_0 / n_t) = k_d$$
 (6.4)

and converted into base 10 logs to achieve

 $\log (n_0 / n_t) = (0.216 / 2.303) *$ 

 $\exp [0.145 * (T_c - 50)]$  (6.5)

Equation 6.5 can be used with time-temperature data to predict the number of decimal reductions  $(D_r)$  that are possible at a given location. The 9 locations in Windrow 1B have been analysed in this manner.

Figures 6.2 through 6.4 show the  $D_r$  at each location over the one week composting period. Most locations have  $D_r$ occurring throughout the composting period. Locations 4, 6,



Figure 6.2: Windrow 1B temperature and log reduction at Locations 1, 2, and 3.



Figure 6.3: Windrow 1B temperature and log reduction at Locations 4, 5, and 6.



Figure 6.4: Windrow 1B temperature and log reduction at Locations 8, 9, and 10.

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8, and 10 show very low values. Figure 6.5 summarizes the  $D_r$  at all 9 locations for the entire composting period. Even Location 4, which has the lowest  $D_r$ , still has a total of 380 over the seven day period.

		380	1180
	3870	7480	3250
1890	3380	1310	510

Figure 6.5: Decimal reductions in Windrow 1B by location.

Calculations of total  $D_r$  do not tell the entire story, however. The effect of micro-organism growth is not included. Problems with unheated, anaerobic zones exist. The effect of mixing on organism survival is similarly not covered. Both of these problems will now be discussed.

Assuming that an nonreacting volume is represented by a sphere, the amount of time that it would take for the temperature at the center of the sphere  $T_0$  to heat to 90 percent of the surrounding mass is calculated. The dimensionless time is given by the Fourier ratio (Fo)

Fo = 
$$(k t / \rho c_p r^2)$$
 (6.6)  
where Fo = Fourier ratio, dimensionless  
 $k =$  thermal conductivity, W / m-s  
 $t =$  time, s  
 $\rho =$  density, kg/m<sup>3</sup>  
 $c_p =$  specific heat, Kj / kg °C  
 $r =$  radius, m

From the Heisler charts (Holman, 1981), the value of the

Fouier number at a dimensionless temperature of 0.9 is 0.3. This is substituted into Equation 6.6 and the equation solved for the time t:

$$t = 0.3 \rho c_p R^2 / k$$
 (6.7)

Selected values of thermal and physical properties covering the range encountered in Windrow 1B are substituted into the above equation and the effect of radius is examined.

Examination of Table 6.3 indicates that unreactive spheres with radii of 5 cm would require less than 2 hours to heat up to 90 % of the surrounding material. Spheres with a radius of 20 cm would take slightly more than a day for the same degree of heating. Large anaerobic compost balls are not expected in DMS solids composting, but it appears that even fairly large spheres could be heated adequately.

Thermal inactivation during composting may also be limited because of non-uniform heat distribution followed by mixing of the compost. Cold pockets could allow pathogenic micro-organisms to survive or regrow. Mixing would then redistribute the organisms throughout windrow or bedding material.

Haug (1980) described the effects of thermal inactivation of pathogens in a two zone windrow. One zone is assumed to have sublethal time-temperature profiles and the other is assumed to have lethal conditions. The windrows are turned at time intervals of  $\Delta t$  and thoroughly mixed so that a random redistribution of compost occurrs.

	of $c$ : ( $\theta$ =	lump diam 0.9).	eter and	thermal	properti	es
Thermal Cond Bulk Density Specific Hea	1. (W, Y (Kg, At (K,	/m-C): /m^3): J/Kg-C):	0.301 696 3.51			0.174 428 3.47
Rać (c	lius cm)	Penetrat (hours)	ion Time (days)	Radius (cm)	Penetrat (hours)	ion Time (days)
( ) 10 19 20 29 50 100	0.5 L.0 5.0 0.0 5.0 0.0 5.0 0.0 0.0	0.02 0.07 1.69 6.76 15.22 27.05 42.27 169.09 676.35	0.001 0.003 0.070 0.282 0.634 1.127 1.761 7.045 28.181	$\begin{array}{c} 0.5\\ 1.0\\ 5.0\\ 10.0\\ 15.0\\ 20.0\\ 25.0\\ 50.0\\ 100.0 \end{array}$	0.02 0.07 1.78 7.11 16.00 28.45 44.46 177.82 711.28	0.001 0.003 0.074 0.296 0.667 1.185 1.852 7.409 29.637
Thermal Cond Bulk Density Specific Hea	1. (W, Y (Kg, at (K,	/m-C): /m^3): J/Kg-C):	0.133 288 3.48			0.071 164 3.47
Rac ( c	lius cm)	Penetrat (hours)	ion Time (days)	Radius (cm)	Penetrat (hours)	ion Time (days)
10 12 21 22 50 100	0.5 1.0 5.0 0.0 5.0 0.0 5.0 0.0 0.0	0.02 0.06 1.57 6.28 14.13 25.12 39.25 156.99 627.97	0.001 0.003 0.065 0.262 0.589 1.047 1.635 6.541 26.165	0.5 1.0 5.0 10.0 15.0 20.0 25.0 50.0 100.0	0.02 0.07 1.67 6.68 15.03 26.72 41.75 166.98 667.93	0.001 0.003 0.070 0.278 0.626 1.113 1.739 6.958 27.831

.+--+ m -£.,, L 1 -C 2 -.... \_ \_ 

The resulting equation is:

$$n_t = n_0 (f_1 + f_h \exp[-kd \Delta t]^N)$$
 (6.8)

where	n+	=	number of organisms surviving
	nč	=	number of organisms initially present
	$f_1^0$	Ξ	fraction of composting material in the low- temperature, sublethal zone
	fh	=	fraction of composting in the high- temperature zone
	Δt	=	time interval between windrow turnings
	<sup>k</sup> d	=	thermal death coeffiecient
	N	=	number of windrow turnings
and	fl	+	$f_h = 1$

Various assumptions about inital pathogen population levels, lethal zone fractions and time temperature thermal death factors are evaluated. Table 6.4 presents the results of such an analysis.

Table 6.4: Effect of initial decimal reduction, fraction of lethal temperature and thermal death coefficent on the number of windrow turns required.

Number of Turns k <sub>d</sub> & t f <sub>1</sub> / f <sub>h</sub> D <sub>r</sub>							
		-2	-3	-4	-5	-6	-7
0.11 0.25 0.50 1.00	2 3 7 8	3 5 10 12	4 6 14 16	5 8 17 20	6 9 20 24	7 10 24 27	
	f <sub>1</sub> / f <sub>h</sub> 0.11 0.25 0.50 1.00	f <sub>1</sub> / f <sub>h</sub> 0.11 2 0.25 3 0.50 7 1.00 8	$\begin{array}{c} f_{1} \neq f_{h} \\ & -2 \\ \hline 0.11 & 2 & 3 \\ 0.25 & 3 & 5 \\ 0.50 & 7 & 10 \\ 1.00 & 8 & 12 \\ \end{array}$	Number $f_1 / f_h$ -2 -3 0.11 2 3 4 0.25 3 5 6 0.50 7 10 14 1.00 8 12 16	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c} \begin{array}{c} \text{Number of Turns} \\ D_r \\ \hline \\ -2 \\ -2 \\ -3 \\ -4 \\ -5 \\ \hline \\ 0.11 \\ 2 \\ 3 \\ -5 \\ 6 \\ 8 \\ 9 \\ 0.50 \\ 7 \\ 1.00 \\ 8 \\ 12 \\ 16 \\ 20 \\ 24 \\ \end{array} \right) $	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$

A  $k_d \Delta t$  value of infinity is assumed for this analysis because of the long one week residence times. The  $k_d \Delta t$ value used in the previous time-temperature curve analysis was approximately 1.5 decimal reductions for a 15 minute period. A range of  $f_1/f_h$  values was used to correspond to different levels of the lethal fraction. The lethal fraction was based on the assumption that each temperature measurement location represented an equal volume in the composting windrow. The 1.0 value results from the assumption that 3 days at 55 C are necessary for safe composting. The 0.25 and 0.11 values for  $f_1/f_h$  correspond to the assumption that temperatures over 50 C resulted in thermal inactivation in Windrows 1 and 2, respectively.

From the results of the analysis presented in Table 6.4, it is apparent that a large number of turns are necessary to achieve thermal destruction by complete mixing of the windrow. If 5  $D_r$  are desired, 5 turnings are required even under the most optimistic assumptions. This analysis would predict that the 3 turnings result in at best 3  $D_r$ .

A number of factors contribute to potential errors in the number of turns analysis. More accurate measurement of the lethal areas improves accuracy. Data developed in this study could provide a first approximation of lethal areas. However, it should be remembered that temperatures in the toe area and on the surface were not adequately monitored.

A major confounding factor is the observation that the degree of substrate consumption could reduce the ability of a windrow to self heat on successive turnings. Finally, the effect of pathogen growth, both at optimal temperatures and on reduced substrates, is not directly included.

Analysis of time-temperature patterns in the compost windrows indicated that there were regions that would have significant reductions of coliform organisms due to long periods of high temperature. There were also windrow regions, however, that had episodes that were in the optimal temperature range for coliform growth. The locations of both regions changed with time, windrow size and windrow shape. The rationale for an improved heat and mass transfer model to predict windrow temperatures is justified.

# 6.5: Application of Composting to Dairy Manure Solids for Production of Bedding Material

At this point I find it hard to advise dairy operators on how best to handle the manure solids, because I collected no microbial evidence to support the deductions based on the time-temperature curves. From a consideration of the timetemperature history alone, I would recommend that dairy operators using this type of windrow composting system should not mix the windrow immediately before using the composted dariy manure solids as bedding material.

Based on the results of the time-temperature curve analysis, I would suggest that at the end of a three week composting period material from the toe area and the unreacted windrow interior should be set aside and the hot composted material should be mixed and used for bedding. The material set aside should be discarded or recycled back into the first week's composting material.

In the long run, enhanced natural or forced convection

may prove to be the methods of choice because of the greater control offered by the forced convection, and the higher composting rate and smaller land requirements of both when compared with a windrow composting system.

Microbial evidence that confirms conclusions based on time-temperature data should receive high research priority. If this evidence becomes available, research to optimize pathogen and substrate reduction in natural or forced convection systems should receive priority over further windrow studies.

# 6.6: Preliminary Assessment of Heat and Mass Transfer Models For Composting Dairy Manure Solids

Without conducting a detailed analysis, the complex unreacted core model discussed earlier appears to describe the observed behavior of this type of composting system very well. The chemical engineering literature contains a large body of information on this subject. This should prove to be a fruitful avenue of exploration to understand the behavior of this type of composting system.

As a first approximation of a heat and mass transfer model, a diffusion based model with spatially varied bulk density and constant moisture content should be considered. The effect of the latent heat of evaporation would be contained in a non-linear k<sub>eff</sub> term. Respiration modeling should include the effects of substrate, oxygen concentration, and temperature on micro-organism growth and inactivation. An accurate unsaturated compaction model for the determination of the spatially varied bulk density, volumetric moisture content and free air space variables that affect heat and mass transfer is essential.

A second generation model that explicitly includes moisture generation and transport relationships would provide a theoretically more accurate picture of windrow processes. Longer term studies would require an unsaturated consolidation model to determine windrow bulk density. The effect of composting on particle size and structural stability should be included in such a model.

Due to observed differences in the penetration depth of the treated dairy manure solids, a model that includes both natural convection and diffusion may be the only acceptable alternative. Due to the formidable requirements of applying this type of model to a windrow, it is suggested that such a model be attempted only after the previously mentioned diffusion based models prove to be inadequate.

### CHAPTER 7

#### CONCLUSIONS

1. The probe design and methods of determining temperature  $(s = \pm 1.5^{\circ}C)$ , gravimetric moisture content  $(s = \pm 2.0 \ \text{wb})$ , and wet bulk density (CV = 11  $\ \text{s}$ ) had acceptable levels of accuracy. Gas concentration determinations were subject to errors caused by gas influx into storage containers. With the use of an empirical correction equation, gas concentrations were accurate to within  $\pm 2$  percent. Volatile solids, whether expressed on a dry or ash basis, had unacceptable measurement errors  $(s_d = 7 \ \text{s})$ .

2. The assumption of constant physical and thermal properties used in previous models is not warranted in all cases. Bulk density, volumetric moisture content and the degree of water saturation increase with depth. Porosity, free air space and the void ratio decrease with depth. Spatial changes in the moisture content (% wb), volatile solids content (% db) and calculated specific heat were not observed. Since many heat and mass transfer properties are related to bulk density, volumetric moisture content and free air space, they should be considered spatially varied. With the methods of measurement used in this experiment,

there was no evidence indicating that bulk density varied with time for this type of compost substrate and windrow system.

3. The dairy manure solids behaved similarly to other composting substrates. Differences exhibited by dairy manure solids composting included the very high moisture contents (between 76 and 81 % wb) and low maximum temperature of 68°C. High moisture content composting occurred because of the high free air spaces caused by dairy manure solid particles. The low temperature could be caused by small windrow sizes, high moisture contents, or long-term substrate limitations. Experimental evidence points toward high moisture content or substrate limitations. Unlike sewage sludge and garbage composting, the expression of moisture content as percent dry basis and volatile solids on a percent ash basis is necessary to detect changes in these parameters.

4. The overall course of the composting reaction behaved like an unreacted core with a reactant being transported into a reactive mass. The observed composting reaction was more complex than a classic unreacted core model as evidenced by the lack of a sharp interface between the spent and fresh solid zones and because of a fast exothermic reaction that produced temperature gradients in the windrow.

5. An estimate of the magnitude of the Thiele modulus was made. The Thiele modulus was not constant throughout the

windrow.

6. Analysis of time-temperature patterns in the compost windrows indicated that there were regions that would have significant reductions of coliform organisms due to long periods of high temperature. There were also windrow regions, however, that had periods of temperature that were in the optimum range for coliform growth. The locations of both regions changed with time, windrow size, and windrow shape.

7. Dairy operators using a windrow compost system should not mix the entire windrow immediately before using the composted dairy manure solids as bedding material. A safer method of handling a three week old windrow of composted dairy manure solids is to set aside material from the windrow toe and central unreacted core for recycling or disposal. The remaining hot composted material can be used for bedding.

8. As a first approximation, a heat and mass transfer model of the dairy manure solids windrow composting process should have the following characteristics:

Diffusion-based Spatially varied bulk density, predicted by an unsaturated compaction model Constant moisture content Respiration modeled with terms accounting for the effect of substrate consumption, temperature and free air space oxygen concentration.

### CHAPTER 8

### DIRECTIONS FOR FUTURE RESEARCH

# 8.1: Experimental Methods

1. <u>Bulk Density.</u> The in situ bulk density of the composting material is a critical parameter that must be accurately measured in any futher work. Together with moisture content, it affects a number of heat and mass transport processes in the compost windrow. Two areas warrant particular study: (a) methods of in-situ measurement of bulk density, and (b), the spatial variance of bulk density as a function of the methods of mixing, placement and turning.

a. <u>In-situ Measurements.</u> There is little discussion of insitu bulk density measurements in the composting literature. The soil and peat sampling literature provided the most fruitful sources of information that lead to the adoption of the bulk density sampling method used in this study. While the rotary corer method gave good repeatability and appeared to give good estimates of bulk density, this needs to be further substantiated. In particular, the effect of drill speed, the possible inclusion or exclusion of dms material in the sample, the effect of methods, rates

and vibration of insertion and the effect of dms particle size and shape on the effective height and radius should be examined.

b. <u>Spatial Variance of Bulk Density</u>. Once accurate methods for in-situ bulk density measurement have been developed, the spatial variance of bulk density as affected by compost substrate, methods of mixing, placement and turning should be investigated. Other investigators have observed that tremendous variations in bulk density beyond those expected due to compost compaction can be present in windrows. Variance estimates the variability are particularly necessary because of the difficulty in taking many bulk density samples during an experiment without affecting heat and mass transfer in the experimental windrow.

2. <u>Moisture Content.</u> Moisture contents expressed on a dry basis give more realistic indications of moisture content changes than wet basis moisture content. The moisture content measurement technique used in this experiment was very time consuming and did not provide frequent measurements. A quicker method could greatly reduce experimental efforts in this area. The development of real time moisture content determinations could complement temperature data measurements. This becomes more crucial in windrow environments with enhanced natural convection or <sup>f</sup>O reed aeration where more rapid moisture content changes can be expected to occur.

3. <u>Substrate.</u> While volatile solids is a commonly used parameter in engineering studies of waste treatment systems, it is a rather crude measurement of substrate consumption. If volatile solids are to be measured in future studies, they should be expressed on an ash solid basis. Future studies should include additional substrate measurements in order to more completely reflect substrate degradation. Levels of amino acids, amino sugars, nitrate and ammonia nitrogen, hemicellulose, cellulose and lignin have been used to measure the degradation of other compost substrates.

# 8.2: Windrow Compost Processes

1. <u>Respiration.</u> The respiratory activity of micro organisms on dms needs to be better understood and quantified. It is doubtful that research on other substrates such a sewage sludge and ground garbage will be transferable beyond providing the general shape of respiration equations. If the dms respiration rate is not quantified, the difficulty in obtaining reasonably accurate estimates of respiration as well as dms heat and mass transfer parameters is greatly increased. The effect of temperature, oxygen and moisture content on respiratory activity needs to be examined. The consumption of various substrate components needs to be measured concurrently.

2. <u>Moisture Content.</u> If moisture content is to be included in a compost windrow model, the role of water in the

composting process must be much better understood. Areas of investigation include the degree of free vs bound water on dms particles as a function of particle size and moisture content; the role of dms compressibility on the extrusion of water from particles to void spaces; and the quantification of water lost to seepage from the windrow base and evaporation from windrow surfaces. The use of tensiometers and relative humidity probes should be evaluated for this purpose.

### 8.3: Compost Heat and Mass Transfer Modeling

1. The development of an unsaturated model of dms windrow compaction is essential to the development of an insitu bulk density sampler and to future modeling efforts. Since bulk density is a key parameter in predicting several heat and mass transfer properties, such a model must be available to predict bulk density.

2. Once the model described above is available, work should proceed with the development and validation of a heat and mass transfer model along the lines suggested in Chapter 7. A second generation model that explicitly includes moisture content would provide a more theoretically sound model. If longer term studies on windrow composting are to be conducted, an unsaturated consolidation model needs to be developed. The effect of the composting process on particle size distributions and dms particle compressibility needs to be investigated and included in the model.

3. Due to the observed differences in the penetration depth of the treated dms, a model that includes both diffusion and natural convection may be the only acceptable alternative. Because of the formidable requirements of applying this type of model to a windrow, it is suggested that such a model be attempted only after the previously mentioned diffusion based models prove to be inadequate. Model development should procede from simpler 1 and 2 dimensional cases before expanding to the complex 3 dimensional situation in dms windrows. APPENDICES

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# APPENDIX A

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# TEMPERATURE MEASUREMENT ERROR CALCULATIONS

# APPENDIX A

### TEMPERATURE MEASUREMENT ERROR CALCULATIONS

The total thermocouple temperature measurement error is the sum of the errors in the reference junction temperature, the thermocouple output, the thermocouple voltage measurement, and the linearization error (difference between standard and polynomial approximations).

A Fenwal Electronics UUT51J1 thermistor mounted in the center of the analog input terminal strip measures the 21X panel temperature. According to the Campbell literature, the "worst case" example adds a  $\pm$  0.3°C error in the range of -35°C to +50°C. In CSI's experience, the overall accuracy is typically better than  $\pm$  0.2°C. The thermistor error increases drastically if temperatures greater than 50°C or less than -35°C are imposed on the CR21X.

Differences between the thermistor and actual reference junction temperature will become errors in measurement. The terminal cover provides a shield to reduce the gradient along the terminal strip. The CR21X manual (Campbell Scientific, 1985) gives an example in which the 21X was brought from -25°C to an ambient temperature of 20°C. After 100 minutes the temperature gradient between the air and the battery is still 15°C, but the deviation from the
measured temperature along the reference strip is only 0.3°C. This taken as the maximum error that could occur in a field situation with proper radiation shielding.

The ANSI standards for thermocouple limits of error are given in the National Bureau of Standards Monograph 125 (1974). For copper constantan thermocouples, they are as follows:

Table A.1: Limits of Error for Thermocouple Wire (Reference Junction at 0°C)

Thermocouple Type	Temp Ran	erat ge °	ure C	( S	Li Which tanda	mits of ever is rd	Error greater) Special
Т	-200	to	0	± 1.0	°C or	1.5 %	± 0.5°C or
	0	to	350	± 1.0	°C or	0.75 %	0.4 %

In order to quantitatively evaluate thermocouple error when the reference junction is not fixed at 0°C, the limits of error for the Seebeck coefficient (slope of thermocouple voltage vs temperature curve) for the various thermocouples must be available. According the CSI, if this information is missing, a reasonable approach is to apply the percentage errors, with perhaps 0.25 % added on, to the difference in temperature being measured by the thermocouple. The temperatures in this experiment will range from 15°C to 70°C. The error due to the thermocouple would be 1.0°C.

The accuracy of a 21X voltage measurement is specified as 0.1 % of the full scale range being used to make the measurement. The error in the temperature due to inaccuracy in the measurement of the thermocouple voltage is worst at temperature extremes, where a relatively large scale is necessary to read the thermocouple output. In the environmental temperature range with voltage measured on an appropriate scale, error in temperature due to the voltage measurements is a few hundredths of a degree (Anonymous, 1985).

Voltage to temperature conversions are accomplished using a proprietary 6th order polynomial. The limit of error on 21X thermocouple output linearization, relative to NBS Standards, is ±0.001 over a range of -100°C to 100°C.

When external reference junction boxes are used errors can arise if the reference junction temperature is outside of the linearization range. The reference temperature compensation range and linearization error relative to the NBS Standards for type T thermocouples are  $-100^{\circ}$ C to  $100^{\circ}$ C and  $\pm 0.001^{\circ}$ C.

The sources of error discussed above are summarized in Table A.2.

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Source	Error (°C)	Percent of Total Error
Reference junction temperature	0.5	32.2
Thermocouple output	1.0	64.4
Voltage measurement	0.05	3.2
Reference linearization	0.001	0.1
Output linearization	0.001	0.1
Total Error	1.552	100.0

Table A.2: Summary of the sources of error in thermocouple measurements.

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#### APPENDIX B

#### SAMPLE THERMOCOUPLE WATER BATH CALIBRATION DATA

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#### APPENDIX B

#### SAMPLE THERMOCOUPLE WATER BATH CALIBRATION DATA

## Table B.1 Water bath thermocouple calibration--Run 1.

		Thermor	יסטיטן				
Hour:Mi	1	2	3	4	5	6	7
1418	-6999	27.86	27.84	27.86	27.86	27.84	27.86
1419	-6999	27.86	27.86	27.87	27.85	27.87	27.86
1420	-6999	27.84	27.82	27.85	27.82	27.84	27.83
1421	-6999	27.82	27.80	27.81	27.80	27.80	27.80
1422	-6999	27.75	27.74	27.75	27.73	27.76	27.75
1423	-6999	27.69	27.68	27.70	27.70	27.70	27.69
1424	-6999	27.64	27.64	27.67	27.65	27.68	27.66
1425	-6999	27.60	27.61	27.62	27.61	27.63	27.62
1426	-6999	27.56	27.57	27.58	27.57	27.59	27.59
1427	-6999	27.53	27.53	27.53	27.52	27.55	27.54
1428	-6999	27.50	27.49	27.50	27.49	27.51	27.51
1429	-6999	27.46	27.46	27.47	27.47	27.47	27.48
1430	-6999	27.41	27.42	27.42	27.42	27.43	27.42
1431	-6999	27.38	27.37	27.38	27.38	27.39	27.38
1432	27.35	27.34	27.33	27.35	27.33	27.36	27.34
1433	-6999	27.30	27.30	27.31	27.30	27.32	27.31
1434	27.26	27.26	27.24	27.27	27.26	27.25	27.26
1435	27.22	27.22	27.20	27.23	27.21	27.22	27.23
1436	27.19	27.17	27.17	27.19	27.18	27.19	27.19
1437	27.12	27.12	27.11	27.12	27.12	27.13	27.13
1438	27.08	27.08	27.08	27.10	27.08	27.09	27.09
1439	27.03	27.04	27.03	27.05	27.03	27.05	27.06
1440	27.03	27.04	27.03	27.06	27.03	27.04	27.06
1441	27.40	27.46	27.42	27.44	27.39	27.41	27.45
1442	27.69	27.71	27.70	27.67	27.71	27.73	27.68
1443	27.66	27.66	27.66	27.67	27.66	27.68	27.68
1444	27.62	27.62	27.61	27.63	27.62	27.64	27.63
1445	27.57	27.58	27.57	27.58	27.57	27.59	27.58
1446	27.52	27.53	27.51	27.53	27.53	27.54	27.54
1447	27.49	27.49	27.49	27.50	27.48	27.50	27.51
Ave.	27.35	27.48	27.48	27.49	27.48	27.49	27.49
Var.	0.05	0.06	0.06	0.06	0.06	0.06	0.06

		Thermoc	ouple				
8	9	10	11	12	13	14	15
27.84	27.89	27.91	27.91	27.94	27.96	27.94	27.94
27.85	27.89	27.92	27.92	27.94	27.95	27.95	27.94
27.84	27.87	27.88	27.89	27.92	27.92	27.92	27.91
27.80	27.84	27.85	27.87	27.88	27.89	27.89	27.88
27.75	27.78	27.80	27.81	27.84	27.84	27.85	27.84
27.68	27.73	27.76	27.77	27.79	27.80	27.80	27.80
27.66	27.70	27.72	27.73	27.77	27.77	27.78	27.78
27.62	27.66	27.69	27.70	27.73	27.73	27.74	27.75
27.58	27.62	27.65	27.66	27.69	27.69	27.72	27.72
27.53	27.58	27.61	27.62	27.64	27.66	27.66	27.67
27.50	27.55	27.57	27.58	27.61	27.62	27.63	27.64
27.47	27.52	27.54	27.55	27.57	27.59	27.61	27.60
27.41	27.46	27.48	27.50	27.52	27.54	27.54	27.55
27.38	27.42	27.45	27.47	27.48	27.49	27.51	27.51
27.33	27.38	27.37	27.38	27.44	27.45	27.45	27.45
27.30	27.35	27.37	27.35	27.40	27.41	27.43	27.40
27.26	27.30	27.32	27.33	27.36	27.38	27.38	27.39
27.21	27.20	27.29	27.30	27.32	27.35	21.34	27.35
27.19	21.22	27.25	27.20	27.28	27.29	27.31	27.31
27.12	27.12	27.10	27.15	21.23	27.24	21.21	21.20
27.05	27.12	27.15	27.10	27.10	27.21	21.22	27.10
27.05	27.03	27.11	27.12	27.13	27.10	27.10	27.17
27.05	27.03	27.00	27.00	27.13	27.13	27.15	27.17
27.69	27.74	27.71	27.73	27.76	27.77	27.81	27.80
27.66	27.71	27.73	27.74	27.78	27.78	27.81	27.80
27.63	27.67	27.68	27.69	27.73	27.74	27.76	27.76
27.57	27.61	27.64	27.65	27.68	27.69	27.71	27.71
27.54	27.58	27.60	27.61	27.64	27.65	27.68	27.68
27.49	27.53	27.55	27.57	27.60	27.60	27.63	27.64
_	_						
27.48	27.53	27.54	27.55	27.58	27.59	27.60	27.60
0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05

Table B.1 (Cont.).

		Thermoc	ouple				
16	17	18	19	20	21	22	23
							•
27.91	27.91	27.99	27.94	27.94	27.94	27.91	27.91
27.95	27.92	28.00	27.95	27.93	27.92	27.94	27.92
27.91	27.91	27.97	27.93	27.91	27.90	27.91	27.91
27.91	27.88	27.96	27.91	27.89	27.87	27.89	27.89
27.85	27.84	27.91	27.86	27.84	27.83	27.84	27.83
27.82	27.80	27.87	27.82	27.80	27.80	27.80	27.79
27.79	27.78	27.85	27.80	27.77	27.76	27.77	27.76
27.75	27.75	27.81	27.75	27.75	27.72	27.74	27.72
27.72	27.72	27.79	27.72	27.70	27.69	27.70	27.69
27.69	27.67	27.74	27.69	27.66	27.65	27.65	27.63
27.65	27.63	27.71	27.64	27.64	27.62	27.62	27.60
27.62	27.60	27.66	27.63	27.59	27.58	27.59	27.57
27.56	27.56	27.63	27.56	27.56	27.53	27.53	27.52
27.53	27.51	27.59	27.53	27.51	27.49	27.50	27.47
27.47	27.47	27.53	27.50	27.47	27.46	27.46	27.44
27.45	27.42	27.49	27.45	27.45	27.41	27.43	27.41
27.40	27.39	27.46	27.41	27.39	27.38	27.38	27.36
27.37	27.35	27.43	27.38	27.36	27.34	27.34	27.32
27.32	27.31	27.38	27.35	27.33	27.31	27.32	27.28
27.28	27.27	27.35	27.31	27.29	27.25	27.26	27.24
27.26	27.23	27.31	27.27	27.24	27.22	27.22	27.21
27.21	27.20	27.27	27.23	27.21	27.18	27.18	27.17
27.21	27.17	27.27	27.22	27.19	27.18	27.17	27.15
27.56	27.46	27.57	27.64	27.59	27.56	27.57	27.54
27.84	27.81	27.90	27.90	27.87	27.86	27.85	27.84
27.84	27.82	27.90	27.85	27.83	27.81	27.81	27.79
27.79	27.78	27.86	27.81	27.78	27.76	27.76	27.74
27.75	27.74	27.81	27.76	27.73	27.71	27.72	27.70
27.70	27.70	27.78	27.70	27.68	27.68	27.66	27.65
27.67	27.65	27.73	27.67	27.64	27.63	27.63	27.60
27.63	27.61	27.68	27.64	27.62	27.60	27.61	27.59
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table B.1 (Cont.).

		Thermoc	ouple				
24	25	26	- 27	28	29	30	31
<del></del>			· · · · · · · · · · · · · · · · · · ·				
27.94	27.91	27.94	27.91	27.91	27.84	31.20	31.37
27.95	27.93	27.92	27.89	27.88	27.84	31.17	31.39
27.91	27.90	27.89	27.88	27.85	27.82	31.17	31.34
27.89	27.87	27.88	27.84	27.82	27.79	31.25	31.44
27.84	27.82	27.82	27.78	27.77	27.73	31.28	31.53
27.78	27.78	27.77	27.72	27.71	27.67	31.26	31.47
27.75	27.74	27.75	27.69	27.68	27.63	31.24	31.47
27.71	27.70	27.71	27.65	27.64	27.60	31.31	31.50
27.68	27.66	27.66	27.60	27.58	27.54	31.25	31.45
27.64	27.62	27.62	27.56	27.55	27.50	31.24	31.40
27.60	27.58	27.58	27.54	27.51	27.47	31.21	31.41
27.57	27.55	27.56	27.50	27.48	27.45	31.25	31.45
27.52	27.51	27.51	27.45	27.44	27.39	31.32	31.50
27.47	27.45	27.47	27.42	27.39	27.35	31.25	31.51
27.45	27.43	27.44	27.37	27.35	27.31	31.35	31.55
27.41	27.39	27.39	27.34	27.31	27.28	31.30	31.58
27.35	27.34	27.34	27.28	27.28	27.22	31.46	31.66
27.33	27.30	27.30	27.25	27.24	27.19	31.44	31.69
27.28	27.28	27.27	27.20	27.19	27.14	31.51	31.64
27.24	27.21	27.21	27.16	27.13	27.09	31.46	31.55
27.20	27.17	27.17	27.12	27.10	27.06	31.49	31.55
27.15	27.14	27.14	27.07	27.06	27.02	31.46	31.49
27.15	27.13	27.12	27.10	27.07	27.01	31.48	31.51
27.54	27.53	27.53	27.50	27.47	27.44	31.48	31.54
27.83	27.82	27.80	27.76	27.74	27.70	31.51	31.58
27.78	27.77	27.76	27.70	27.69	27.64	31.51	31.58
27.74	27.71	27.71	27.65	27.63	27.60	31.51	31.56
27.68	27.67	27.67	27.61	27.59	27.56	31.56	31.61
27.64	27.61	27.62	27.57	27.54	27.50	31.59	31.64
27.60	27.58	27.57	27.52	27.50	27.47	31.51	31.57
27.59	27.57	27.57	27.52	27.50	27.46	31.37	31.52
0.06	0.06	0.06	0.06	0.06	0.06	0.02	0.01

## Table B.1 (Cont.).

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32	Ave.	Var.	S.D.
31.59	27.91	0.002	0.040
31.61	27.91	0.002	0.040
31.61	27.88	0.002	0.039
31.03	27.00	0.002	0.043
31.03	21.01	0.002	0.040
31.03	21.10	0.003	0.053
31.04	21.13	0.003	0.058
31 66	27.05	0.003	0.050
31 66	27.03	0.004	0.004
31.68	27.57	0.004	0.062
31.70	27.54	0.004	0.061
31.70	27.49	0.004	0.061
31.71	27.45	0.004	0.061
31.72	27.41	0.004	0.060
31.73	27.37	0.003	0.058
31.74	27.33	0.004	0.062
31.75	27.29	0.004	0.064
31.76	27.26	0.004	0.064
31.76	27.20	0.005	0.070
31.77	27.17	0.005	0.068
31.78	27.13	0.005	0.070
31.78	27.12	0.004	0.065
31.79	27.48	0.005	0.069
31.80	27.78	0.005	0.068
31.80	27.75	0.005	0.070
31.81	27.70	0.005	0.070
JI.02	21.00	0.005	0.003
JI.0J	21.01 27 57	0.005	0.072
JT.03	41 <b>.</b> 31	0.005	0.070
31.72	27.56	.00	0.06
0.01	0.06	.00	.00

#### APPENDIX C

# EFFECT OF SEQUENTIAL GAS SAMPLES AND LOCATION ON CARBON DIOXIDE AND OXYGEN CONCENTRATION

#### APPENDIX C

## EFFECT OF SEQUENTIAL GAS SAMPLES AND LOCATION ON CARBON DIOXIDE AND OXYGEN CONCENTRATION

#### Table C.1: Effect of sequential gas samples and location on CO2 and O2 concentrations.

Sequential Volume	Loca	tion 1	Loca	tion 5	Loca	tion 8	Locat	ion 10
withdrawn	C02	02		02	C02	02	C02	
5	0.63	19.54	0.80	18.54			0.27	16.64
15	7.85	12.64	9.02	10.17	3.40	16.06	16.38	5.82
25	7.80	13.01	15.95	4.65	4.40	16.40	19.08	3.96
35	7.82	13.11	16.87	3.81	4.00	15.73		
45	7.61	12.75	15.73	5.63	4.22	16.33	18.63	4.99
55	7.37	12.95	15.44	2.96	4.03	16.30	19.32	4.06
65	7.78	13.49	15.66	4.36			20.05	3.49
75	7.94	13.23	16.04	4.61	2.62	16.87	19.12	3.87
AVG *	7.74	13.03	15.95	4.34	4.16	16.19	19.24	4.07
SD	0.18	0.27	0.46	0.82	0.16	0.27	0.46	0.50
CV	2.29	2.05	2.86	18.87	3.86	1.65	2.41	12.18

\*Statistics are calculated from the linear portion of the data.

## APPENDIX D

## GAS CONCENTRATION CORRECTION FACTOR CALCULATIONS

#### APPENDIX D

#### GAS CONCENTRATION CORRECTION FACTOR CALCULATIONS

The procedures used to determine the gas concentration correction factor due to withdrawal of samples from the "venoject" sample containers with a syringe prior to injection into the gas chromatograph were described in general in Chapter 4. This appendix describes in more detail the procedures and calculations used to arrive at these results.

The experiment consisted of evacuating six 3 cc venojects and filling them to an initial pressure of 1.5 atmospheres. This duplicated the inital conditions of sample storage in the main experiment. 1.05 cc withdrawals were made from each venoject and injected into the gas chromatograph to check for the oxygen concentration. The lengths were recorded and oxygen concentrations were calculated based on a four point calibration curve. The presence of any oxygen was assumed to be due to oxygen present in the syringe tip before sample withdrawal, diffusion of oxygen into the syringe needle after withdrawal or the flow of ambient air into the syringe due to a pressure difference. The initial lengths of the gas chromatograph traces and the calculated oxygen

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concentrations are shown in Table D.1 and Table D.2. The calibration curve is given at the bottom of Table D.2.

The internal pressure of the sample container and syringe were calculated for several pressures, sample container volumes and syringe volumes. The equation used in this calculation was

$$P_{f} = (P_{i} * V_{c})/(V_{c} + V_{s})$$
 (D.1)

where P<sub>x</sub> = internal pressure of x, atmospheres
V<sub>y</sub> = volume of y, cubic centimeters
f = final
i = initial
c = sample container
s = sample syringe

For example, if the initial conditions were 1.5 atmospheres, 3 cc and 1.05 cc for the initial pressure, container volume and sample volume, respectively, the final internal pressure is

 $P_f = 1.50 * 3.00 / (3.00 + 1.05) = 1.11$  atmospheres The results of these calculations are shown in Table D.3.

Plotting the calculated internal pressure for each sample withdrawn against the measured oxygen concentration indicated two linear segments. These were shown in Figure 4.9 of the text.

Influx was calculated by assuming that the initial and atmospheric oxygen concentrations were 0.0 and 20.9 percent, respectively. Equation D.2 was used:

$$O_{\rm m} = {\rm In} * O_{\rm e} + F * O_{\rm a} \qquad (D.2)$$

where  $O_x = oxygen$  concentration at x, percent

1	2	Replic 3	cation 4	5	6	AVG	STD	CV
1.90 2.25 5.85 8.40	1.30 2.30 6.50 9.00	1.55 2.95 6.50 9.10	1.40 2.70 6.45 9.10 11.10 12.40	2.30 3.70 7.15 8.70 11.80 13.00	1.75 2.85 6.85 9.90 11.45 12.70	1.70 2.79 6.55 9.03 11.45 12.70	0.34 0.48 0.40 0.46 0.29 0.24	19.73 17.29 6.09 5.10 2.50 1.93
D.2:	Oxyger withdr	n conce cawal n	entrat: number	lons a: . *	sa fui	nction	of	
1	2	Replic 3	cation 4	5	6	AVG	STD	cv
0 1.56 1.92 6.06 9.37	0 0.99 1.97 6.88 10.19	0 1.22 2.66 6.88 10.32	0 1.08 2.39 6.82 10.32 13.11 14.99	0 1.97 3.49 7.72 9.78 14.12 15.86	0 1.42 2.55 7.33 11.43 13.61 15.42	0.00 1.37 2.50 6.95 10.24 13.62 15.43	0.33 0.52 0.51 0.63 0.41 0.36	23.89 20.97 7.32 6.16 3.01 2.32
	1 1.90 2.25 5.85 8.40 D.2: 1 0 1.56 1.92 6.06 9.37	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c cccccc} & \text{Replication} \\ 1 & 2 & 3 & 4 \\ \hline 1.90 & 1.30 & 1.55 & 1.40 \\ 2.25 & 2.30 & 2.95 & 2.70 \\ 5.85 & 6.50 & 6.50 & 6.45 \\ 8.40 & 9.00 & 9.10 & 9.10 \\ & & 11.10 \\ & & & 12.40 \\ \hline \\ $	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Replication123456AVG1.901.301.551.402.301.751.702.252.302.952.703.702.852.795.856.506.506.457.156.856.558.409.009.109.108.709.909.0311.1011.8011.4511.4511.4512.4012.4013.0012.7012.7012.70Replication123456AVG00000.001.560.991.221.081.971.421.371.921.972.662.393.492.552.506.066.886.886.827.727.336.959.3710.1910.3210.329.7811.4310.2413.1114.1213.6113.6214.9915.8615.4215.43	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$

Table D.1: Gas chromatograph trace length as a function of withdrawal number.

\* Calibration equation:  $02 = 0.7217 * L^{-1.2048}$ 

Table D.3: Eff	ect of in	itial pre	ssure, sa	mple cont	ainer
vol	ume, and	sample si	ze on sam	ple conta	iner and
syr	inge inte	rnal pres	sure afte	r samplin	g.
Init. Press.:	1.500	1.375	1.250	1.125	1.000
Stor. Vol.:	4.00	4.00	4.00	4.00	4.00
Sample Vol.:	0.55	0.55	0.55	0.55	0.55
SAMPL NUMBE	E P R	RESSURE A (Atmos	FTER SAMP pheres)	LE	
0	1.500	1.375	1.250	1.125	1.000
1	1.319	1.209	1.099	0.989	0.879
2	1.159	1.063	0.966	0.869	0.773
3	1.019	0.934	0.849	0.764	0.679
4	0.896	0.821	0.747	0.672	0.597
5	0.788	0.722	0.656	0.591	0.525
6	0.692	0.635	0.577	0.519	0.462
7	0.609	0.558	0.507	0.457	0.406
8	0.535	0.491	0.446	0.401	0.357
Init. Press.:	1.500	1.375	1.250	1.125	1.000
Stor. Vol.:	4.00	4.00	4.00	4.00	4.00
Sample Vol.:	1.05	1.05	1.05	1.05	1.05
SAMPL NUMBE	E P R	RESSURE A (Atmos	FTER SAMP pheres)	LE	
0	1.500	1.375	1.250	1.125	1.000
1	1.188	1.089	0.990	0.891	0.792
2	0.941	0.863	0.784	0.706	0.627
3	0.745	0.683	0.621	0.559	0.497
4	0.590	0.541	0.492	0.443	0.394
5	0.468	0.429	0.390	0.351	0.312
6	0.370	0.340	0.309	0.278	0.247
7	0.293	0.269	0.245	0.220	0.196
8	0.232	0.213	0.194	0.174	0.155

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Table D.3: (cont	t'd.).				
Init. Press.:	1.500	1.375	1.250	1.125	1.000
Stor. Vol.:	3.00	3.00	3.00	3.00	3.00
Sample Vol.:	0.55	0.55	0.55	0.55	0.55
SAMPLI NUMBEI	E P R	RESSURE A (Atmos	FTER SAMP pheres)	LE	
0	1.500	1.375	1.250	1.125	1.000
1	1.268	1.162	1.056	0.951	0.845
2	1.071	0.982	0.893	0.803	0.714
3	0.905	0.830	0.754	0.679	0.604
4	0.765	0.701	0.638	0.574	0.510
5	0.646	0.593	0.539	0.485	0.431
6	0.546	0.501	0.455	0.410	0.364
7	0.462	0.423	0.385	0.346	0.308
8	0.390	0.358	0.325	0.293	0.260
Init. Press.:	1.500	1.375	1.250	1.125	1.000
Stor. Vol.:	3.00	3.00	3.00	3.00	3.00
Sample Vol.:	1.05	1.05	1.05	1.05	1.05
SAMPL NUMBE	E P R	RESSURE A (Atmos	FTER SAMP pheres)	LE	
0	1.500	1.375	1.250	1.125	1.000
1	1.111	1.019	0.926	0.833	0.741
2	0.823	0.754	0.686	0.617	0.549
3	0.610	0.559	0.508	0.457	0.406
4	0.452	0.414	0.376	0.339	0.301
5	0.335	0.307	0.279	0.251	0.223
6	0.248	0.227	0.206	0.186	0.165
7	0.184	0.168	0.153	0.138	0.122
8	0.136	0.125	0.113	0.102	0.091

Substituting known values and rearranging, we get

$$In = O_m / 20.948$$
 (D.3)

Figure 4.9 of the text shows influx for the 3cc sample container as a function of internal pressure. Table D.4 includes the calculated average 3cc influx values  $(In_3)$  for this experiment.

Table	D.4:	Low error	intermediate
		calculatio	ons.

Sample Number	Vol Removed	P4	02M	In3	In4
0	0.00	1.500	0.0	0.000	0.000
1	1.05	1.111	1.3	0.066	0.049
2	2.10	0.823	2.5	0.119	0.089
3	3.15	0.610	7.0	0.332	0.249
4	4.20	0.452	10.2	0.489	0.366
5	5.25	0.335	13.6	0.650	0.487
6	6.30	0.248	15.4	0.736	0.552

The 3 cc results were converted to those for a 4 cc container by (a) converting the 3 cc fractional influx to a volume influx and (b) calculating the fraction of 4 cc that was represented by (a). For samples of 1.05 cc, the 3 cc fractional value was 0.066, the volume was 3 \* 0.066 = 0.198, and the 4 cc fractional volume was 0.198 / 4 =

0.0495. These results are also shown in Table D.4.

The calculated internal pressures that corresponded to the volume withdrawn from the 3 cc sample container were used with the 4 cc influx values in a linear regression. In Table D.4, the pairs of numbers corresponding to the sample numbers 0, 1 and 2 in columns 3 and 6 were used for Y and X, respectively. The calculated pressures from the 3 cc container were used for the same sample number from a 4 cc container because it was the pressure conditions in the 3 cc container that produced the calculated pressure. The equation developed (r = 0.9996) was

 $In_{4P} = -7.619 * P_{f} + 1.495$  (D.4) Next, a linear regression was run with the withdrawal number and the assumed internal pressure of a 4 cc container (P<sub>4</sub>) as X and Y respectively. The resulting equation (r = 0.9971) was

 $P_A = -0.1508 * S + 1.4802$  (D.5)

Using Equation D.5,  $P_4$  values for the main experiment sample numbers were caclutaed. The results of this calculation are shown in Table D.5. The influx into a 4 cc container was calculated using the output of the previous step and Equation D.4. A linear regression was performed on the In<sub>4</sub> as X and S as Y. The equation developed (r = 1.000) was

 $In_4 = 0.01977 * S + 0.002$  (D.6)

This equation was used to calculate influx values as a function of the sample withdrawal number.

Sample	Low Error		High 3	Error
Number	P4	In4	P4	In4
	1 480	0 0020	0 9868	0 0000
1	1.329	0.0218	0.8862	0.0914
2	1.179	0.0415	0.7856	0.1726
4	0.877	0.0811	0.5844	0.3417

Table D.5: Final gas correction calculations.

In order to develop a worst case analysis, it was assumed that the worst situation would occur if the sample gas leaked out of the container to the point where the internal pressure was at one atmosphere. In this situation, the removal of gas with the syringe would immediately produce a relative vacuum in the syringe and influx of ambient air would occur. It was further assumed that the worst case was represented by the second linear section of the pressure vs. measured oxygen curve (Figure 4.9).

The calculation procedure was similar to that of the previous error calculation. The fractional influx was determined and the 3 cc influxes were converted to 4 cc influxes. As in the small error case, the calculated  $P_3$  was assumed to be the cause of the gas transport and a linear regression was run on In<sub>4</sub> and P<sub>4</sub> (= P<sub>3</sub>). The data used corresponded to the rows with sample numbers 3 to 6 in Table D.4. The resulting equation (r = 0.9976) was

 $P_4 = -1.160 * In_4 + 0.8934$  (D.7)

Since all gas under pressure was assumed to have escaped the sample container in this worst case scenario, the initial pressure was assumed to be 1.0 atmospheres. The linear regression of sample numbers and internal pressure used the values corresponding to the calculated pressures in a 4 cc sample container initially at 1.0 atmosphere with sequential 0.55 cc syringe samples being withdrawn. These values are shown in Table D.3.

The equation that resulted from this regression was

 $In_4 = -1.160 * S + 0.9868 (r = -0.9971) (D.8)$ New values of the 4 cc internal pressure were calculated using this equation. The results are shown in Table D.5.

The slope of Equation D.8 was assumed to be accurate and the "a" term was adjusted so that at S = 0, the influx would be zero. The resulting equation was

 $In_4 = (P_4 - 0.9868) / -1.166 \quad (D.9)$ New values of the influx were calculated using the above equation and the results are shown in Table D.5.

A linear regression was run on the sample number and the  $In_4$  influxes and the following equation (r = 1.000) was developed:

 $In_4 = 0.0851 * S + 0.0027$  (D.10) This equation was used to assess the high error case.

For a given sample volume the effect is linear and can be described as follows for each gas:

$$O_a = O_m - In * O_e / F$$
 (D.11)

 $C_a = C_m / F$  (D.12)

where all terms are as defined before.

Data on the sample number of each gas measurement were available. With this, the measured concentrations, Equations D.6 and D.10 for the low and high influx calculations, and Equations D.11 and D.12 for the actual oxygen and carbon dioxide, the actual gas concentrations could be calculated.

In order to provide sample calculations a number of combinations of gas concentration and sample withdrawal numbers are shown in Table D.6. Three combinations of carbon dioxide and oxygen concentrations with high, medium and low levels of each gas are shown in this table. Withdrawal numbers ranging from 1 to 3 are included. Most sample withdrawal numbers in the study were either 1 or 2; only a few were 3. As can be seen from the calculated concentration columns in Table D.6, the correction equations do adjust the concentrations in the correct direction and larger withdrawal numbers do lead to greater influxes and larger adjustments to the concentrations. One drawback is that the sum of the calculated concentrations is affected by the starting concentration and the number of withdrawals, with lower  $CO_2$  and higher withdrawal numbers lowering the sum of the two calculated concentrations.

Two additional estimates of gas concentration corrections were examined. The third estimate was to take the "average" of the low and high influx error estimates. This was intended to approximate the uncertainty that the

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C02	02	Withdrawal Number	Influx Eqn	Influx	Calu CO2	clated 02	Sum
17 12 2 17 12 2 17	4 9 19 4 9 19	1 1 2 2 2 3	D.6 D.6 D.6 D.6 D.6 D.6 D.6 D.6	0.022 0.022 0.022 0.042 0.042 0.042 0.042 0.061	17.4 12.3 2.0 17.7 12.5 2.1 18.1	3.5 8.5 18.5 3.1 8.1 18.1 2.6	20.9 20.8 20.6 20.8 20.6 20.2 20.2 20.7
12 2	9 19	3 3	D.6 D.6	0.061 0.061	12.8 2.1	7.6 17.6	20.4 19.8
17 12 2 17 12 2 17 12 2	4 9 19 4 9 19 4 9	1 1 2 2 2 3 3 3 3	D.10 D.10 D.10 D.10 D.10 D.10 D.10 D.10	0.088 0.088 0.091 0.091 0.091 0.093 0.093 0.093	18.6 13.2 2.2 18.7 13.2 2.2 18.7 13.2 2.2	2.0 7.0 17.0 1.9 6.9 16.9 1.8 6.8 16.8	20.6 20.1 19.2 20.6 20.1 19.1 20.6 20.1 19.1
17 12 2 17 12 2 17 12 2	4 9 19 4 9 19 4 9	1 1 2 2 3 3 3 3	Average Average Average Average Average Average Average Average		18.0 12.7 2.1 18.2 12.9 2.1 18.4 13.0 2.2	2.8 7.8 17.8 2.5 7.5 17.5 2.2 7.2 17.2	20.8 20.5 19.9 20.7 20.4 19.6 20.7 20.2 19.4
17 12 2 17 12 2 17 12 2 2	4 9 19 4 9 19 4 9 19	1 1 2 2 2 3 3 3 3	CO2 Co CO2 Co CO2 Co CO2 Co CO2 Co CO2 Co CO2 Co CO2 Co CO2 Co	rrect rrect rrect rrect rrect rrect rrect rrect	17.0 12.0 2.0 17.0 12.0 2.0 17.0 12.0 2.0	3.9 8.9 18.9 3.9 8.9 18.9 3.9 8.9 18.9	20.9 20.9 20.9 20.9 20.9 20.9 20.9 20.9

Table D.6: Gas concentration calculations.

exact initial pressure in the sample container was unknown. The fourth estimate was based on the assumption that the measured carbon dioxide value was correct and that the oxygen concentration was equal to 20.95 % minus the measured carbon dioxide concentration.

Increases in carbon dioxide concentration at high measured concentrations were 1.6 % for the high influx correction, 1.0 to 1.4 % for average influx, and 0.4 to 1.0 % for the low influx correction. Increases at low measured carbon dioxide concentrations were less than 0.2 percent.

Oxygen concentration corrections achieved by the high, average, and low influx calculations were all less than the measured values. The largest corrections occurred at the lower measured concentrations. The high influx correction resulted in an approximately 2 % calculated oxygen decrease from measured concentrations of 4 percent. The corresponding decreases for the average and low influx calculations were 1.2 to 1.8 % and 0.5 to 1.4 % respectively. Corrected oxygen concentrations obtained from the fourth method tended to be higher than the measured concentrations by as much as 1 % oxygen.

The low influx correction is based on the assumption that all gas samples were placed in the cylinders at the same pressure and no gas leaked out. The high influx assumes that all gas at pressures over 1 atmosphere leaked out. As indicated in Chapter 4 of the text, the assumptions underlying both these methods are open to question. The

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initial pressure under which gas was inserted into the sample containers was unknown. Preliminary experiments also indicated that there was some leakage out of the storage system but that uncovered samples did not decrease to 1 atmosphere pressure in the two week period before they were analyzed. All that can be said, therefore, about the internal sample container pressure at the start of analysis is that it was between 1.0 and 1.5 atmospheres. The fourth correction method was abandoned because it did not result in the desired corrections.

The average influx calculation was chosen for use because of the uncertainty over the internal sample pressure at the start of analysis. This method is not without its problems, however. In realistic conditions, the actual influx would be governed by the low influx correction until the internal pressure fell below 1.0 atmospheres, at which time the high influx equation would apply. Since the initial pressure is unknown and the number of samples that could be withdrawn before the high influx conditions would prevail is therefore uncertain, the average influx calculation is the best compromise that can be achieved. APPENDIX E

## VOLUMETRIC GAS STANDARDS ERROR CALCULATIONS

#### APPENDIX E

#### VOLUMETRIC GAS STANDARDS ERROR CALCULATIONS

Two of the four standards used in calibrating the gas chromatograph were made up volumetrically. The following discussion describes the procedure that was used and the error calculations that were made.

The standards were made using 160 cc sample bottles with rubber caps. The capped bottles were evacuated using a vacuum pump and then filled with pure nitrogen gas. This procedure was repeated 3 times with the sample bottles being left in the vacuum state. Oxygen, carbon dioxide and nitrogen were then added by gas syringes of different sizes to make up the desired concentrations at 2 atmospheres of pressure. Two syringe sizes were used: 30 cc and 60 cc. The two syringes had variances of 0.5 and 1 cc respectively. Table E.1 summarizes the concentrations and numbers of syringe fillings that were needed for each concentration. The calculation for gas concentration in percent has the form

 $G_{c} = 100 * V_{i} / V_{t}$  (E.1) where  $G_{c} =$  gas concentration, percent V = Volume, cc i = ith gas

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Standard Number	Gas Conce <sup>CO</sup> 2	l Co	Numbe:	r of s	Syrin <sup>D</sup> 2	ge Us	es <sup>N</sup> 2	
	(perc	(percent)		60	30	60	30	60
3	10	10	2	0	2	0	1	4
4	20	1	1	1	1	0	1	4

Table E.l: Concentration and syringe use data.

t = Total

Applying the product rule for the propagation of errors (See Appendix G), we have

$$s_{g} = [(\partial G_{c}^{2} / \partial V_{i}^{2}) * s_{i}^{2} + (\partial G_{c}^{2} / \partial V_{t}^{2}) * s_{t}^{2}]^{0.5}$$
(E.2)

Taking the paritial derivatives of Equation E.1 with respect to  $V_i$  and  $V_t$  we get values of  $(100/V_t)$  and  $(100V_i/T^2)$  respectively. Values of the variance for  $V_i$  and  $V_t$  are arrived at by multiplying the individual variance of each syringe by the number of times that syringe is used.

The variance of the 10 % CO<sub>2</sub> standard can be calculated as follows:

 $v_{i} = 2 * 0.5 cc = 1.0 cc$   $v_{t} = [2 * 0.5 cc] + [2 * 0.5 cc] + [4 * 1.0 cc$  + 1 \* 0.5 cc] = 6.5 cc  $s_{CO2}^{2} = [(100/320)^{2} * (1.0) + (100*32/(320^{2}))^{2} * (6.5)]$  = 0.104 %

The variance for the oxygen concentration of standard 3 is

the same as that for carbon dioxide. Variances of standard 4 are 0.1719 % and 0.049 % for carbon dioxide and oxygen, respectively.

## APPENDIX F

### PRELIMINARY BULK SAMPLER EXPERIMENTS

#### APPENDIX F

## PRELIMINARY BULK SAMPLER EXPERIMENTS

Table F.1: Effect of sampler type and sample depth on calculated bulk density, porosity and free air space.

TYPE	DEPTH	4	REPLICATI 5	I ON 7	AVG	STD DEV	CV
		Moi	sture Con	ntent			
RING	1 2 3	80.6 82.1 81.6	81.4 83.0 81.1	81.8 81.2 81.7	81.3 82.1 81.5	0.49 0.72 0.26	0.006 0.009 0.003
AVG STD CV		81.4 0.61 0.007	81.8 0.83 0.010	81.6 0.24 0.003			
SHORT	1 2 3	81.0 80.8 82.6	81.4 81.0 80.7	81.9 81.8 80.9	81.4 81.2 81.4	0.36 0.43 0.85	0.004 0.005 0.010
AVG STD CV		81.5 0.83 0.010	81.1 0.26 0.003	81.5 0.42 0.005			
LONG	1 2 3	79.6 80.3 80.1	80.9 81.2 80.7	81.9 81.6 81.4	80.8 81.0 80.7	0.91 0.54 0.53	0.011 0.007 0.007
AVG STD CV		80.0 0.28 0.004	80.9 0.19 0.002	81.6 0.18 0.002			

TYPE	DEPTH	4	REPLICAT:	ION 7	AVG	STD Drv	cv
		Vola	atile So	lids			
RING	1	93.5	94.3	94.4	94.0	0.42	0.004
	2	94.8	94.6	94.8	94.7	0.09	0.001
	3	93.8	94.9	94.7	94.5	0.50	0.005
AVG		94.0	94.6	94.6			
STD		0.56	0.25	0.17			
CV		0.006	0.003	0.002			
SHORT	1	94.1	95.0	94.3	94.5	0.36	0.004
	2	94.9	94.9	94.3	94.7	0.26	0.003
	3	94.8	95.0	94.2	94.7	0.37	0.004
AVG		94.6	95.0	94.3			
STD		0.33	0.06	0.07			
CV		0.004	0.001	0.001			
LONG	1	94.3	94.6	94.4	94.4	0.15	0.002
	2	94.5	94.0	94.5	94.3	0.21	0.002
	3	94.4	94.6	93.7	94.3	0.38	0.004
AVG		94.4	94.4	94.2			
STD		0.09	0.28	0.34			
CV		0.001	0.003	0.004			

TYPE	DEPTH	4	REPLICAT 5	TON 7	AVG	STD Dev	CV
		Full E	ag Weigh	t (gm)			
RING	1 2 3	467.50 460.70 500.20	495.80 556.20 446.50	413.75 492.50 508.80			
SHORT	1 2 3	296.33 425.91 447.10	317.43 409.90 408.50	311.67 371.03 454.30			
LONG	1 2 3	221.08 237.26 291.44	192.38 224.72 312.68	189.91 216.72 276.08			
		Net Sol	ids Weig	ht (gm)			
RING	1 2 3	458.00 451.20 490.70	486.30 546.70 437.00	404.25 483.00 499.30			
SHORT	1 2 3	286.83 416.41 437.60	307.93 400.40 399.00	302.17 361.53 444.80			
LONG	1 2 3	211.58 227.76 281.94	182.88 215.22 303.18	180.41 207.22 266.58			
			Length	(in)			
RING	1 2 3	2.0 2.0 2.0	2.0 2.0 2.0	2.0 2.0 2.0	2.0 2.0 2.0	0.00 0.00 0.00	0.000 0.000 0.000
SHORT	1 2 3	12.0 11.5 9.5	12.0 12.5 7.0	12.0 12.0 6.5	12.0 12.0 7.7	0.00 0.41 1.31	0.000 0.034 0.171
LONG	1 2 3	13.0 10.5 10.0	12.5 12.5 10.0	14.0 10.0 10.0	13.2 11.0 10.0	0.62 1.08 0.00	0.047 0.098 0.000

TYPE	DEPTH	4	REPLICAT 5	'ION 7	AVG	STD CV DEV
		Bulk D	ensity	(kg/m^3)		
RING	1 2 3	278 274 298	295 332 265	245 293 303	273 300 289	20.7 0.076 24.1 0.080 16.7 0.058
AVG STD CV		283 10.5 0.037	297 27.2 0.092	281 25.2 0.090		
SHORT	1 2 3	198 300 382	213 265 472	209 250 567	206 272 474	6.1 0.030 21.0 0.077 75.7 0.160
AVG STD CV		293 75.1 0.256	317 112.0 0.354	342 160.1 0.469		
LONG	1 2 3	202 270 350	182 214 377	160 258 331	181 247 353	17.2 0.095 23.9 0.097 18.7 0.053
AVG STD CV		274 60.6 0.221	258 85.4 0.331	250 70.1 0.281		

TYPE	DEPTH	4	REPLICATI 5	ION 7	AVG	STD CV DEV
			Porosity	7		
RING	1 2 3	0.967 0.884 0.964	0.964 0.859 0.969	0.971 0.876 0.964	0.967 0.873 0.965	0.003 0.003 0.010 0.012 0.002 0.002
AVG STD CV		0.938 0.039 0.041	0.930 0.050 0.054	0.937 0.043 0.046		
SHORT	1 2 3	0.976 0.962 0.957	0.974 0.967 0.941	0.975 0.970 0.930	0.975 0.967 0.942	0.001 0.001 0.003 0.003 0.011 0.012
AVG STD CV		0.965 0.008 0.008	0.961 0.014 0.015	0.959 0.020 0.021		
LONG	1 2 3	0.973 0.965 0.955	0.977 0.974 0.953	0.981 0.969 0.960	0.977 0.969 0.956	0.003 0.003 0.003 0.004 0.003 0.003
AVG STD CV		0.964 0.008 0.008	0.968 0.011 0.011	0.970 0.009 0.009		

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TYPE	DEPTH	R 4	EPLICAT	ION 7	AVG	STD CV DEV	
		Free	Air Spa	ace			
RING	1 2 3	0.741 0.743 0.721	0.724 0.688 0.752	0.770 0.726 0.716	0.745 0.719 0.730	0.019 0.026 0.023 0.032 0.016 0.022	
AVG STD CV		0.735 0.010 0.013	0.721 0.026 0.036	0.737 0.023 0.032			
SHORT	1 2 3	0.815 0.720 0.641	0.801 0.752 0.559	0.805 0.766 0.471	0.807 0.746 0.557	0.006 0.007 0.019 0.026 0.070 0.125	
AVG STD CV		0.726 0.071 0.098	0.704 0.104 0.148	0.681 0.149 0.219			
LONG	1 2 3	0.812 0.749 0.674	0.830 0.800 0.648	0.850 0.759 0.690	0.831 0.769 0.671	0.015 0.019 0.022 0.029 0.017 0.026	
AVG STD CV		0.745 0.057 0.076	0.760 0.080 0.105	0.766 0.065 0.085			
COMPARISON	STD DEV RATIO *	F RESULT (95%)		POOLED STD DEV	STUDENI T	<b>!</b>	SIGNIF LEVEL
----------------	--	---------------------	-------------------	--------------------------	----------------------	-------------------	-----------------
	Bulk De	ensity					
Ring/ Short	25.3/7.529 29.519/25.772 20.414/92.956	11.3 1.3 16.0	nsd nsd nsd	40.00 29.13 114.60	2.03 1.18 1.98	nsd nsd nsd	95 95 95
Ring/ Long	25.3/21.07 29.519/29.258 20.414/22.845	1.4 1.0 1.2	nsd nsd nsd	54.20 38.98 40.16	2.07 1.65 1.96	nsd nsd nsd	95 95 95
Short/ Long	7.529/21.070 25.772/29.258 92.956/22.845	7.8 1.3 16.6	nsd nsd nsd	19.83 28.08 89.61	1.54 1.07 1.65	nsd nsd nsd	95 95 95
	Free Air	Space					
Ring/ Short	0.0233/0.007 0.0282/0.0236 0.0195/0.085	11.1 1.4 19.0	nsd nsd sd	0.037 0.028 0.110	2.04 1.20 1.94	nsd nsd nsd	95 95 95
Ring/ Long	0.0233/0.019 0.0282/0.027 0.0195/0.212	1.2 1.1 1.2	nsd nsd nsd	0.058 0.037 0.037	2.08 1.66 1.95	nsd nsd nsd	95 95 95
Short/ Long	0.007/0.019 0.0236/0.027 0.085/0.0212	7.4 1.3 16.1	nsd nsd nsd	0.018 0.026 0.083	1.61 1.08 1.68	nsd nsd nsd	95 95 95

Table F.2: Statistical analysis of bulk density and free air space data.

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 Larger standard deviations placed on top for calculations. n = 3 for all treatments.

APPENDIX G

DERIVATION OF ERROR PROPAGATION EQUATIONS

### APPENDIX G

### DERIVATION OF ERROR PROPAGATION EQUATIONS

Assume that u = f(x, y) and that all errors are independent and may be treated as random. Further assume that all deviations  $\delta x_i = x_i - x$  and  $\delta y_i = y_i - y$  are relatively small. Applying the Taylor series expansion, neglecting higher order terms, we have

$$u_{i} = f([x + \delta x_{i}], [y + \delta y_{i}])$$
  
=  $f(x,y) + \frac{\partial u}{\partial x} * \delta x_{i} + \frac{\partial u}{\partial y} * \delta y_{i}$  (G.1)

and,

$$\delta u_i = u_i - u = \frac{\partial u}{\partial x} \delta x_i + \frac{\partial u}{\partial y} \delta y_i$$
 (G.2)

By definition, the square of the standard deviation in u,  $s_u$ , is  $s_u^2 = \sum (\delta u_i)^2 / n$  (G.3) Squaring G.2 gives  $(\delta u_i)^2 = (\frac{\partial u}{\partial x})^2 (\delta x_i)^2 + 2 \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} \delta x_i \delta y_i + (\frac{\partial u}{\partial y})^2 (\delta y_i)^2$ (G.4) Placing this expression into G.3, we have  $s_u^2 = (\frac{\partial u}{\partial x})^2 \sum (bx_i)^2 + 2 \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} \sum (bx_i by_i) + (\frac{\partial u}{\partial y})^2 \sum (by_i)^2$ n (G.5)

As n increases, the sum  $(\delta x_i \delta y_i)$  goes to 0 if  $x_i$  and  $y_i$  are independent because any  $bx_i$  by is likely to be positive as negative. Since

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$$s_x^2 = \Sigma(\delta x_i)^2 / n \text{ and } s_y^2 = \Sigma(\delta y_i)^2 / n (G.6)$$

can be substituted into G.5 to get

$$s_u^2 = (\frac{\partial u}{\partial x})^2 s_x^2 + (\frac{\partial u}{\partial y})^2 s_y^2$$
 (G.7)

For more than 2 terms, G.7 can be generalized to

$$s_u^2 = \Sigma(\frac{\partial u}{\partial x_i})^2 s_{xj}^2$$
 (G.8)

The fractional variance in U is written by dividing  $s_u$  by u:

$$(s_u / \overline{u})^2 = (\Sigma(\frac{\partial u}{\partial x})^2 s_{xj}^2) / \overline{u}^2$$
 (G.9)

The fractional variance should not be used unless the 0 of each  $x_i$  and u scales are physically significant (Parrot, 1961).

Sum or Difference

Let  $u = x \pm y$ 

then

$$\frac{\partial u}{\partial x} = 1$$
 and  $\frac{\partial u}{\partial y} = \pm 1$ 

substituting into G.8, we have

$$s_u^2 = s_x^2 + s_y^2$$
 (G.10)

The fractional standard deviation is

$$(s_{u} / \overline{U})^{2} = (s_{x}^{2} + s_{y}^{2}) / \overline{U}^{2}$$
 (G.11)

Product or Quotient

Let

$$u = x_a + y_b \qquad (G.12)$$

with a and b assumed to be exact constants. Then

$$\frac{\partial u}{\partial x} = ax^{a-1}y^b$$
 and  $\frac{\partial u}{\partial y} = bx^ay^{b-1}$  (G.13)

Substituting the above equation into equation G.8, we

have

$$s_u^2 = a^2 x^{2(a-1)} y^{2b} s_x^2 + b^2 x^{2a} y^{2(b-1)} s_y^2$$
 (G.14)

The fractional variance of a product is given by

$$(s_{u} / U)^{2} = (a^{2}x^{2a-2}y^{2b}s_{x}^{2} / U^{2}) + (b^{2}x^{2a}y^{2b-2}s_{y}^{2} / U^{2})$$
  
=  $(a^{2}x^{2a-2}y^{2b}s_{x}^{2} / \overline{x}^{2a}\overline{y}^{2b}) + (b^{2}x^{2a}y^{2b-2}s_{y}^{2} / \overline{x}^{2a}\overline{y}^{2b})$   
=  $(a^{2s}x^{2} / \overline{x}^{2}) + (b^{2}s_{y}^{2} / \overline{y}^{2})$  (G.15)

# APPENDIX H

# WINDROW SIZE, TEMPERATURE, GAS CONCENTRATION AND PHYSICAL PROPERTY SAMPLING LOCATIONS AND DATA AVAILABILITY

### APPENDIX H

## WINDROW SIZE, TEMPERATURE, GAS CONCENTRATION AND PHYSICAL PROPERTY SAMPLING LOCATIONS AND DATA AVAILABILITY

Complete data on windrow size, temperature and ambient conditions, gas concentration and physical properties are available from the author at the following address:

Stephen E. Ferns c/o Dr. John Gerrish Department of Biological and Agricultural Engineering A.W. Farrall Hall East Lansing, Michigan 48823 USA

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The data has the following formats and requirements: Temperature: Symphony (1) 7 360 KB floppy disks; Windrow Elevations, Gas Concentrations, and Physical Properties: Lotus 123 (1A) 2 360 KB floppy disks.

Please send the necessary disks and disk mailer with your request.

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