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**EXPERIMENTAL VERIFICATION OF THE NATURAL CONVECTIVE TRANSFER
OF AIR THROUGH A COMPOSTING MEDIA**

By

Andrew Charles Fogiel

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ABSTRACT

EXPERIMENTAL VERIFICATION OF THE NATURAL CONVECTIVE TRANSFER OF AIR THROUGH A COMPOSTING MEDIA

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An experimental apparatus was developed capable of allowing the measurement of airflow through a passively aerated composting media. The chamber was used to verify that natural convection is the primary mechanism of aeration in such systems. Measured air velocities were checked against models based on (1) Darcian flow through a porous media, (2) process kinetics, and (3) air required to account for moisture lost during the process. A stoichiometric oxygen demand model was applied to check the oxygen content measurements against the estimated amount of carbon consumed during the process.

Air velocities predicted using process kinetics were closest to measured air velocities. This model and the moisture removal based model could only be applied to stages of the composting process that were near or at steady-state. Darcian flow based model underestimated the actual measured airflow and did not account for changes in moisture, bulk density, and overall compost mass. The stoichiometric demand model used roughly estimated oxygen needed to consume a known quantity of carbon was comparable to levels measured during the process.

To my family.

ACKNOWLEDGEMENTS

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Finally to my family in Delaware and in France, and my friends across the United States, for always being there through the good, the bad, and the ugly. I am especially grateful that my Mom was into backyard composting before I was born. Her support had no boundaries even when the “chips” were down. My biggest critic and at the same time, biggest supporter, has been and will always be my Dad. Although to him making a living in composting just does not make any sense, he has never questioned and has always encouraged my desire to excel as a researcher, teacher, pupil, and son.

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LIST OF SYMBOLS

A = cross sectional area of compost container, m^2

Ar = content of argon = 0.009 (atmospheric)

c_{pa} = specific heat of ambient air, kJ/kg

c_v = specific heat of vapor for dew point temperatures, $kJ/kg-K$

C_{lost} = mass of carbon lost, kg carbon

CO_2 = content of carbon dioxide measured (produced) in compost, %

$C_pH_qO_rN_s \cdot aH_2O$ = organic matter

$C_tH_uO_vN_w \cdot cH_2O$ = compost

dH_2O = water evaporated

eH_2O = water produced

bO_2 = oxygen consumed

g = acceleration of gravity, m^2/sec

h_c = heat of combustion of materials, kJ/kg

HAO = enthalpy of outlet air, kJ/kg

HAI = enthalpy of inlet air, kJ/kg

k = rate of disappearance of dry matter (decomposition rate), day^{-1}

K = permeability of the porous medium, m^2

L = length of compost column, m

L_v = latent heat of vaporization, kJ/kg

$m(\theta)$ = dry mass of compost at time θ , kg

m_e = equilibrium dry mass, kg

m_o = initial dry compost mass, kg

$m(\theta)$ = dry mass of compost at time θ , kg

mR = compost mass ratio

M = mass of air required, kg dry air/kg dry compost

M_{dc} = mass of oven-dried compost and crucible, g

M_{ac} = mass of ash and crucible, g

M_c = mass of crucible, g

MC_{wb} = moisture content, wet basis, %

M_{wc} = mass of wet compost and container (pie plate), g

M_{dc} = mass of dry compost and container (pie plate), g

M_c = mass of container (pie plate), g

n = number of moles of air

N = content of nitrogen = 0.78 (atmospheric)

O_2 = content of oxygen measured in compost, %

OM_o = initial organic matter content, kg

$OM(\theta)$ = organic matter at time θ , kg

OM = organic matter content, percent

ΔP = pressure drop across length L

P = pressure (assumed atmospheric) = 101.3 kPa

$PAIR$ = atmospheric pressure, mm Hg

PVS = saturation water vapor pressure, mm Hg

q = volumetric air flow rate, m^3/sec

$Q(\theta)$ = total airflow at time θ , m^3/day

R = universal gas constant

T = Temperature of air, K

ΔT = temperature difference between ambient air and compost air, °C

V = volume of air, m³

v = average velocity over time θ

w_{as} = saturated moisture content of air, kg/kg

w_a = moisture content of air, dry basis, kg/kg

w_{ak} = moisture content of compost, dry basis, kg/kg

w_{ako} = initial moisture content of compost, wet weight basis, kg

$w_{ak}(\theta)$ = moisture content of compost at time θ , wet weight basis, kg

W = amount of moisture removed over time θ , kg water/kg dry compost

θ = time, day

μ = fluid viscosity, kg/m/s

u = specific volume of air, m³/kg

v = air velocity, m/s

ρ_c = density of air in compost, kg/m³

$\rho_a = \rho$ = density of air, kg/m³

ρ_{ai} = density of air at inlet, kg/ m³

ω = specific humidity, kg water/kg dry air

ω_{exit} = specific humidity of exit air, kg water/kg dry air

ω_{inlet} = specific humidity of inlet air, kg water/kg dry air

CHAPTER 1

INTRODUCTION

1.1 Overview of Composting

Composting has gained significant attention as a means of diverting a variety of organic materials from the waste stream and recycling them into a finished product with many benefits to the soil environment. Compost improves soil tilth, fertility, moisture holding capacity, infiltration, resistance to erosion, and reduction in diseases. But many challenges face the composting industry especially in dealing with the dynamics and complexities associated with handling and processing large amounts of organic residuals. These challenges are expected to only increase as a higher variety of organic materials are diverted from landfills and recycled through composting.

1.1.1 Definition

There is no universally accepted definition for composting, but basically it is the practice of controlling and optimizing a naturally occurring biological process in which aerobic microorganisms decompose various organic materials to yield carbon dioxide gas, heat, water, and a stable, soil-like product called humus, or compost. Understanding the biological aspects of composting is beneficial for making sound management and operational decisions in controlling and optimizing the composting process.

1.1.2 Critical Factors

Factors critical to managing the composting process include quality of the feedstocks, moisture, aeration, and temperature. Optimizing the composting process requires being able to control these critical factors as much as possible and is the challenge to developing best management strategies. On-farm composting management strategies are based largely on practical experience and relative to most other farming practices have received little scientific study. There is a need for improved understanding of the overall process on order that researchers can study ways of optimizing the overall process.

1.2 Aeration

Aeration in naturally and passively aerated composting systems is assumed to occur by convection (Lynch et al. 1995, Haug 1993). Researchers have observed and reported compost mixtures that went anaerobic within hours of initial mixing and following turning of the material (Lufkin et al. 1995, Haug 1993, Miller et al. 1989). If the compost mixture does not provide adequate aeration, the oxygen demand of aerobic microorganisms is sufficient to deplete the oxygen resulting in increased anaerobic microbial activity. Anaerobic activity leads to the production of a variety of odorous compounds, and odor control is a significant management challenge.

Materials at the outer edge of a windrow or pile decompose at a much slower rate than materials within the windrow or pile. Also, heterogeneity in moisture, temperature, and oxygen concentration occur in piles. Turning the compost is necessary for mixing

the materials and for ensuring uniform decomposition. It is widely believed that turning provides sufficient aeration for composting, but that is no longer the case.

There is a need to investigate methods that will improve aeration and at the same time reduce the machinery needs and overall amount of energy input to the composting process. Turning the compost often comes down to availability of time rather than trying to optimally managing the process (Rynk 1992).

1.3 Modeling

Scientifically based modeling and application to managing the composting process has been mostly limited to forced aerated composting systems. Naturally aerated composting which is most commonly used in on-farm composting situations has seen limited application of modeling in improving the operation and management of the process. Such models are difficult to nearly impossible to verify due to the fact that lower than measurable air velocities are predicted to be entering a naturally aerated composting medium (Lynch et al. 1995, Michel et al. 1995, Haug 1980 and 1993, Miller et al. 1989).

The inability to measure and quantify the air velocity parameter alone has been the hurdle in verifying process modeling of a naturally aerated composting process. Until progress can be made in this area, improvements of how the composting process is managed will continue to be done the way it has been done for thousands of years, by trial and error.

CHAPTER 2

OBJECTIVES

1. Develop an experimental apparatus capable of measuring airflow through a passively aerated composting media.
2. Verify that natural convection is the primary mechanism for aeration through a passively aerated composting media.

CHAPTER 3

LITERATURE REVIEW

3.1 Overview of the Composting Process

Composting is the practice of managing and optimizing a naturally occurring biological process in which aerobic microorganisms decompose organic materials to yield carbon dioxide gas, heat, water, and a stable, soil-like product called humus, or compost. If the process goes anaerobic, offensive odors are generated which can lead to problems with neighboring communities. Understanding the composting process is very important for making proper management decisions in ensuring odors are minimized, the process is optimized, and resulting end product is of maximum quality.

In nature, dead plant and animal matter is decomposed slowly into humus primarily by microorganisms that are widely distributed in the environment. The rate at which these microorganisms decompose organic materials to humus depends on the relative amounts of carbon and nitrogen in the material mix, the availability of oxygen, environmental factors such as temperature and moisture, and on physical factors such as particle size of the materials being consumed.

The overall objective in managing the composting process is to create and maintain an optimal environment for specific microbial communities to decompose organic matter as efficiently and as fast as possible. Management of the composting process requires proper mixing of materials based on the ratio of carbon to nitrogen (C:N

ratio) in the input materials, periodic monitoring of factors such as compost temperature, moisture, and oxygen and/or carbon dioxide levels.

As aerobic decomposition occurs, carbon is lost as carbon dioxide gas, and nitrogen is conserved. The higher rate of carbon loss results in a decrease of the C:N ratio of the mixture. The volume of the composting material is reduced by 50 to 60% while the weight is reduced by 40-80% mostly due to moisture loss (Rynk 1992). The pH varies depending on feedstocks, but optimum decomposition by thermophilic bacteria has been found to occur in mixtures with a pH range of 7.5 to 8.5 (Epstein 1997). Michel et al. (1995) reported an increase of pH during composting of leaf, grass, and brush mixtures, but pH can both increase and decrease during composting depending on the feedstock mixture (Rynk 1992).

If oxygen is lacking during composting the process will go into anaerobic decomposition, or fermentation. Aerobic decomposition converts organic matter into carbon dioxide gas, water, and heat, while nitrogen is converted into nitrate. If the pH rises above 7.5 to 8.0, ammonia will also be released. Anaerobic decomposition converts organic matter into carbon dioxide gas, methane gas, various alcohol compounds, and volatile fatty acids (VFA's), nitrogen is converted to ammonia, and sulfur compounds are converted to hydrogen sulfide gas.

Anaerobic zones will likely form in particles within well managed compost piles or windrows (Atkinson et al 1996, Hamelers 1993, Haug 1993). If the interstitial O₂

content falls below 5% the composting process will start to go anaerobic (Rynk 1992). The VFA's, ammonia, and hydrogen sulfide gas are all odorous products. The odors are released when the windrows are turned and can create problems for a facility located near commercial or residential areas. It is unreasonable to think composting can be conducted without generating some odors. But these odors can be minimized through properly mixing the feedstocks and managing to ensure that adequate aeration, moisture, and temperature are maintained throughout the composting process.

Diffusion of oxygen plays a significant role in particle kinetics (Hamelers 1993). Its role during the process is limited to supplying oxygen to particles provided sufficient interstitial oxygen levels are maintained (Epstein 1997, Haug 1993, Miller et al. 1989). The size of the particles play a significant role in the overall process kinetics (Haug 1993).

Particle sizes of 1.0 cm were predicted to have large diffusion resistances that would result in the formation of anaerobic zones within the particle during the process (Hamelers 1993, Haug 1993). Particle sizes on the order of 0.1 cm and lower were predicted to be small enough that oxygen diffusion equals the rates of oxygen demand (Haug 1993). But such small particle sizes would become a physically limiting factor for supplying oxygen to a windrow or pile (Lynch et al. 1995, Haug 1993). Therefore, a balance of particle size is required to meet the particle oxygen demand while providing adequate pore space for aeration.

3.2 Microbiology of Composting

Composting is a process carried out primarily by microorganisms that decompose organic materials. The major groups of microorganisms that are active during composting are bacteria, actinomycetes, and fungi. Each group has diverse members that function under a variety of environmental conditions. A summary of these microorganisms is given in Table 3.1.

Microbial groups are also classified based on the temperature ranges in which they are active. Mesophilic microbes are active from 10°C to 50 °C, and thermophilic microbes are active from 45 °C to 70 °C. Most organic matter breakdown occurs at thermophilic temperatures, but microbial activity will rapidly decrease if temperatures exceed 70 °C (Rynk 1992).

Table 3.1. Description of primary microorganisms in composting (Rynk 1992)

Microbial Group	Description
Bacteria	Microscopic organisms that are very simplistic and can exist in a variety of forms and environmental conditions. Most numerous group of microorganisms active during composting and generally considered the fastest decomposer.
Fungi (molds)	Larger than bacteria, more tolerant of low-moisture and low-pH conditions, but less tolerant of low-oxygen conditions. Decompose woody substances and other decay-resistant materials better than bacteria.
Actinomycetes	Similar in structure to fungi, but they are actually bacteria. Primarily aerobic, more pronounced after easily degraded compounds are gone and when moisture and temperature is low.

Temperature is one of the main indicators of microbial activity. A typical temperature trend observed in a properly managed compost windrow over the first 50 days of composting is shown in Figure 3.1. Ranges in which mesophilic and thermophilic microbes thrive are indicated. Bacteria flourish in the early stages of composting consuming the easily degraded materials.

Fungi and actinomycetes become most active near the end of composting consuming materials that are more difficult to consume. Bacteria will dominate composting as long as conditions are favorable. Fungi gain an advantage at low pH, while low-moisture favors both fungi and actinomycetes.

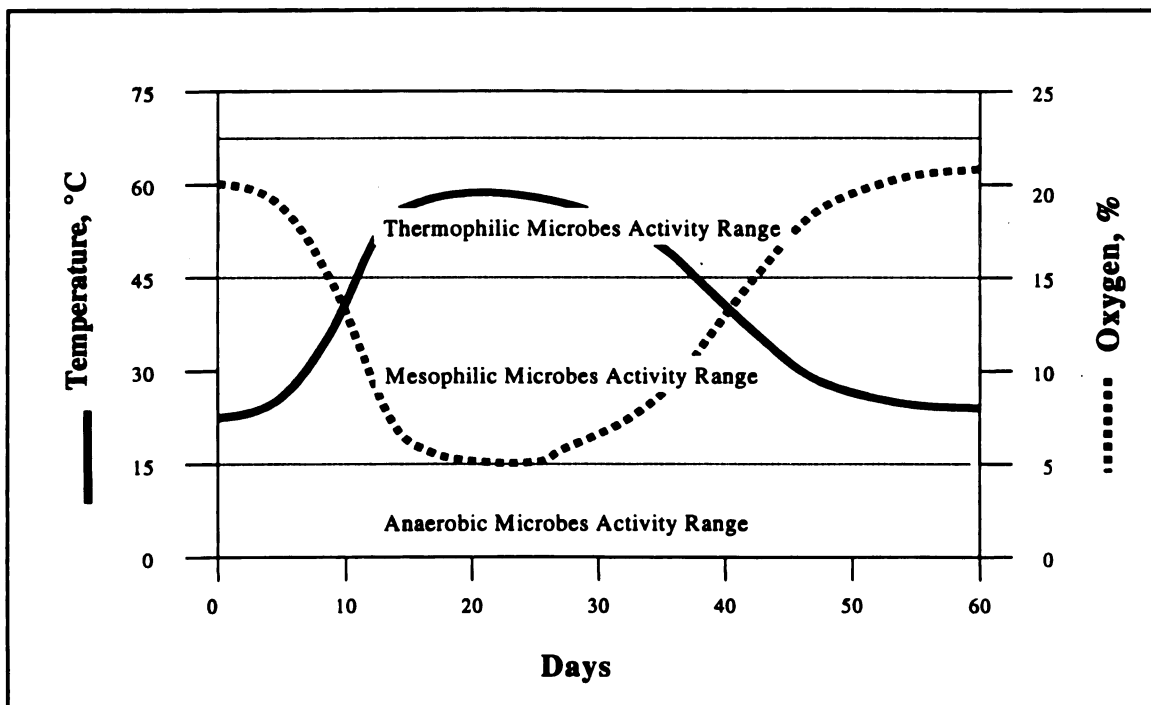


Figure 3. 1. Idealized Temperature Profile (adapted from Epstein, 1997)

Optimum C:N ratios vary depending on the materials composted, but the generally accepted range is 25:1 to 30:1 (Rynk 1992). The composting process can be

adversely affected if there is excessive or insufficient carbon or nitrogen. Microorganisms utilize carbon for energy and growth and nitrogen is a vital source of protein and essential for reproduction.

Moisture is important for the metabolic processes of the microbes. The generally accepted range of moisture is 40-65 percent on a wet weight basis. The water provides the medium required for chemical reactions and transport of nutrients. Excessive water content is detrimental because it displaces air in the pore spaces of the composting material leading to oxygen diffusional limitations and anaerobic conditions.

3.3 Composting Methods

A large portion of the scientific understanding of the compost process has come from composting high-water content materials such as sewage sludge and certain manure (Haug 1993). These materials are typically composted in enclosed or in-vessel systems that allow near-complete control of moisture, aeration, and temperature. Enclosed composting systems are typically expensive and unfeasible compared to windrow and pile composting systems for applications where the volume of the materials are high, the moisture contents are relatively low, and adequate land space is available.

3.3.1 Windrow Composting

One of the most common methods for on-farm composting is windrow composting (Rynk 1992). In windrow composting, a raw mixture of organic materials is placed in elongated, trapezoidal piles called windrows. Windrows with the proper

dimensions and structure are thought to aerate naturally by a chimney effect or convection (Figure 3.2) where rising heat generated inside the pile draws in cooler air from the bottom and sides of the windrow.

Turning windrows decreases particle size, releases carbon dioxide, and blends the composting material to enhance uniform decomposition and weed seed kill. Until recently, turning was also thought to be a significant source of oxygen during composting. But researchers have found that a majority of the oxygen introduced at turning is used by microbial respiration within only hours (Lufkin et al. 1995, Michel et al. 1995). Therefore, the primary mechanism of oxygen transfer into windrows is convection

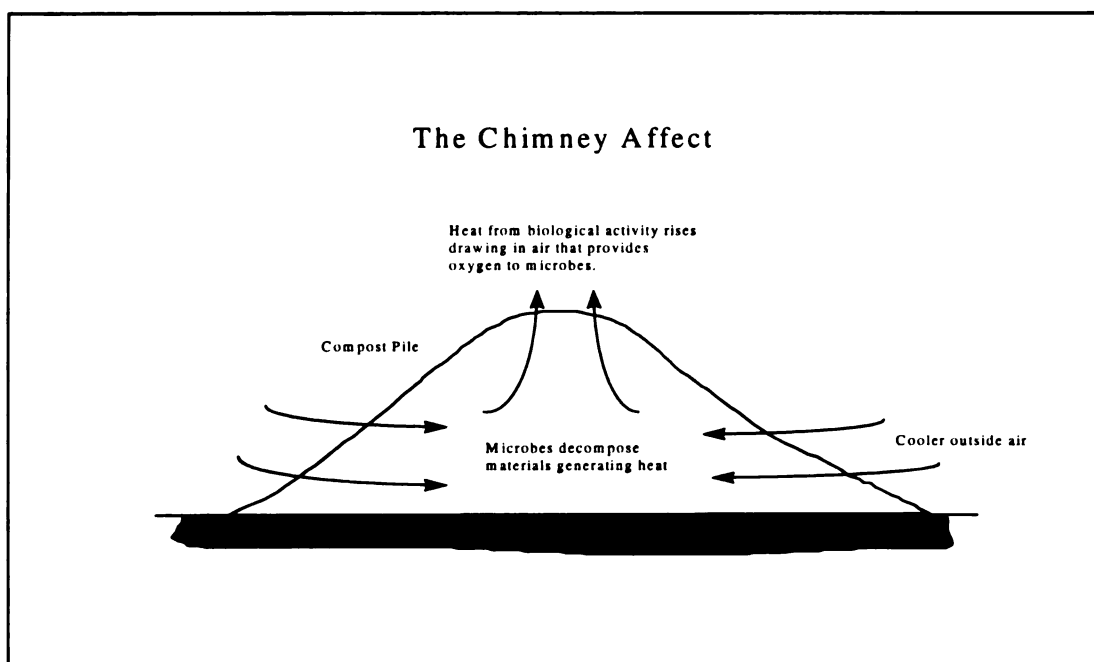


Figure 3. 2. Schematic of the Chimney Affect (adapted from Haug 1993)

3.3.2 Passively Aerated Windrow Composting

An adaptation of the windrow method is called passively aerated windrow composting. The experimental apparatus developed for and the overall scope of this study was based on the passively aerated windrow and pile method described by Lynch et al (1995), and a low-velocity, forced aeration apparatus developed and used by Das et al. (1997).

In passively aerated windrow composting, perforated pipes are inserted at specific locations long the base of compost piles or windrows enhancing aeration through the composting media. The windrows or piles are formed on a porous base such as gravel or straw into which the pipes are inserted. Passively aerated windrow composting is preferred when less turning is desired or when the feedstock materials are wetter than desirable for windrow composting (greater than 65% wet weight moisture content). However, the raw materials require more thorough initial mixing, and if ambient air is relatively dry, conserving moisture during the process will become a management challenge.

Sartaj et al. (1997) compared the performance of forced, passive, and natural aeration methods for composting manure slurries. Passive aeration had a similar process rate to forced aeration and both methods were quicker than the natural aeration method. Passive aeration was found to provide adequate oxygen without adversely cooling the process, involved less labor, and was more effective in conserving nitrogen than forced

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aeration. Passive aeration maintained high process temperatures ($>55^{\circ}\text{C}$) longer than both the forced and natural aeration methods.

Further understanding of naturally and passively aerated windrow composting is needed over a wider variety of feedstock materials and different mixtures. The use of models in the design and engineering of these systems has been limited by the inability to verify these models. This is primarily due to the inability to measure and quantify the relatively low air velocities associated with natural convective airflow (Lynch et al., 1995, Michel et al., 1995, Haug 1993, Keener et al., 1993, Miller et al., 1989).

3.4 Modeling

Several numerical models have been developed in order to better understand the behavior of the composting process (Das et al. 1997; Strombaugh et al. 1996; Lynch et al. 1995; Haug 1993; Hamelers 1993; Keener et al. 1993). With the exception of the Lynch et al. (1995) model, a majority of the models are based on forced aeration and not natural convection.

Haug (1993) developed one of the most detailed computer simulation models of the composting process, but is mostly limited to in-vessel systems in which moisture, air and temperature can be controlled directly. These factors are nearly impossible to manage with aeration windrow composting systems. But many of the fundamental concepts of the aerobic composting process developed by Haug (1993) can be applied to a naturally or passively aerated composting process.

3.4.1 Modeling Natural Convection Processes

Naturally and passively aerated windrow systems have been demonstrated to be feasible, but the design and engineering procedures are not easily extended to different pile configurations or mixtures of feedstock materials (Lynch et al. 1995; Haug 1993). Unlike forced aeration systems, verifying models of the naturally and passively aerated composting process has been difficult due to the low ventilation velocities predicted by natural convection models (Lynch et al. 1995; Michel et al. 1995; Haug 1993; Miller et al. 1989).

Aeration in windrow composting is one of the most important aspects and challenges in properly managing the composting process and is also one of the least understood. Aeration in passively and naturally aerated windrow composting is thought to occur primarily through the natural convective movement of air caused by the heating of the composting media. Haug (1980) developed a complicated hydraulic model to simulate the process of natural ventilation in a composting media, but reported that it was virtually impossible to develop an experiment to verify the natural ventilation process.

Researchers have only been able to imply that convection is the primary mechanism by which oxygen is supplied into a naturally aerated composting (Michel et al. 1995; Lynch et al. 1995; Haug 1993; Miller et al. 1989; Fermor et al. 1985). Verification of composting models has therefore been limited to systems employing forced aeration.

Models published by Lynch et al. (1995), Haug (1993), and Keener et al. (1993) were used to evaluate the data collected in this study and to verify that natural convection was the primary mechanism of aeration. A simple stoichiometric model based on respiration was developed and also used for data evaluation.

3.4.2 Modeling Compost Aeration Based on Darcian Flow Through a Porous Media

Lynch et al. (1995) developed a model for passively aerated compost piles which have porous pipes placed at the base to enhance aeration. The model follows the flow of air first into and exiting the porous pipes, and second vertically through the compost pile itself. The second part, airflow in the vertical direction, was the initial focus and foundation of this study.

The Lynch et al. (1995) model is based on Darcy's Law written as

$$v = -\frac{K}{\mu} \frac{(\Delta P)}{(L)} \quad (3.1)$$

Where

v = air velocity

μ = fluid viscosity

K = permeability of the porous medium

L = length of compost column

ΔP = pressure drop across length L

The pressure difference ΔP is the driving force of natural convection on and when expressed in terms of difference in air densities between the heated compost air and the cooler ambient air has the form

$$\Delta P = (\rho - \rho_c)gL \quad (3.2)$$

Where

ρ = density of air entering the base of compost, kg/m^3

ρ_c = density of air in compost, kg/m^3

g = acceleration of gravity, m^2/sec

Lynch et al. (1995) assumed the temperature of the compost (T_c) and consequently ρ_c are constant throughout the pile. Density of air can be estimated using the Ideal Gas Law in the form

$$\rho = \frac{1}{v} = \frac{P}{nRT} \quad (3.3)$$

Where

ρ = density of air, kg/m^3

v = specific volume of air, m^3/kg

P = pressure (assumed atmospheric) = 101.3 kPa

n = number of moles of air

R = universal gas constant = $8.3145 \text{ kPa} \cdot \text{m}^3 / \text{mol} \cdot \text{K}$

T = Temperature of air, K

(add a subscript “c” to ρ and T terms to express compost air)

The effect of water vapor is significant to the difference in densities between ambient air and air within the compost (Lynch et al. 1995). Bach et al. (1987) found that air leaving compost piles is saturated when the compost is at a moisture content greater than 50%, and is at 95% when compost moisture contents were in the range of 45 to 50%.

Haug (1993) and Hamelers (1993) assumed air exiting compost forced aeration systems to be saturated which greatly simplified analytical and numerical modeling of the aerobic composting process. Assuming air exiting a naturally aerated composting media is saturated simplifies the estimation of exit air density from exit air temperature.

Air density can also be expressed as a function of oxygen and carbon dioxide content through the universal gas constant R. Based on the standard chemical composition of atmospheric air (Weast 1982), R can be solved with the form

$$R = \frac{8.314}{(N \times 28 + Ar \times 40 + O_2 \times 32 + CO_2 \times 44)} \quad (3.4)$$

Where

R = universal gas constant, kPa · m³/ kg · K

N = content of nitrogen = 0.78 (atmospheric)

Ar = content of argon = 0.009 (atmospheric)

O₂ = content of oxygen measured in compost

CO₂ = content of carbon dioxide measured in compost

The permeability factor (K) can be obtained by measuring the pressure drop (ΔP) across a length of a column (L) packed with compost, as a function of air velocity (v),

and rearranging Darcy's Law (Equation 1) to solve for K. Published information for permeability (K) of various composting mixtures and how it is affected by factors such as particle size, bulk density, and moisture content of the compost media is limited.

3.4.3 Modeling Compost Aeration Based on Compost Kinetics

Keener et al. (1993) derived a complex set of analytical expressions that demonstrate the interdependence between biological and physical factors. Equations are developed based on energy and mass balances for a composting system. Modeling of the compost process kinetics is limited to the first stage of composting which is the time when substrate is most readily available for microbial decomposition.

The following assumptions were made in developing the equations:

- 1) Temperature of compost air equals temperature of compost material at a given location,
- 2) Temperature of air leaving a control volume is temperature within the volume,
- 3) No compost crosses the boundaries of the control volume,
- 4) Heat loss from system due to conduction and radiation is zero,
- 5) Compost mass is maintained at a moisture level > 45 percent, and
- 6) Air leaving system is saturated.

During the first stage of composting, the rate of biomass reduction was assumed to be a first order reaction. This rate of disappearance equation is written as

$$\frac{dm(\theta)}{d\theta} = -k(m(\theta) - m_e) \quad (3.5)$$

Where

θ = time, day

$m(\theta)$ = dry mass of compost at time θ , kg

m_e = equilibrium dry mass, kg

k = rate of disappearance of dry matter (decomposition rate), day^{-1}

The dry equilibrium mass, m_e , represents the amount of materials which remain after a long period of composting, typically taken at 6 months to 1 year and includes the mass of both ash and organic matter. Decomposition of the organic matter by microorganisms at this point is assumed to be limited.

The decomposition rate, k , can be derived from experimental data. If k is constant, the solution of equation takes the form:

$$mR = \frac{m(\theta) - m_e}{m_o - m_e} = -e^{-k\theta} \quad (3.6)$$

Where

mR = compost mass ratio

m_o = initial dry compost mass, kg

The compost mass ratio is a dimensionless number used to describe how far the process has advanced relative to the final equilibrium mass, m_e . Although published information on values of k is limited, k varies greatly with different types of materials (Keener et al. 1993).

Heat generated during composting was related to the enthalpies of air entering and exiting the process under steady state conditions, and the heat generated by substances, termed heat of combustion. Aeration becomes important in terms of maintaining process temperatures. Without adequate aeration, the heat generated can accumulate and bring process temperatures above optimal conditions ($> 65\text{ }^{\circ}\text{C}$) and microbial activity will rapidly decrease slowing the composting process.

Keener et al. (1993) developed an expression for the theoretical airflow rate required for maintaining a constant temperature during the composting process. Based on the energy balance at steady state conditions for a constant flow adiabatic process, the theoretical air flow rate is given by

$$q = \frac{-kh_c}{[HAO - HAI]} \quad (3.7)$$

Where

q = volumetric air flow rate, m^3/sec

h_c = heat of combustion of materials, kJ/kg

HAO = enthalpy of outlet air, kJ/kg

HAI = enthalpy of inlet air, kJ/kg

The expression in the denominator in equation 3.7 is the difference between inlet and outlet air enthalpies, and is solved by

$$[HAO - HAI] = c_{pa} + (c_v w_{as}) \Delta T + L_v (w_a - w_{ak}) \quad (3.8)$$

Where

c_{pa} = specific heat of ambient air, kJ/kg

c_v = specific heat of vapor for dew point temperatures, kJ/kg-K

w_{as} = saturated moisture content of air, kg/kg

ΔT = temperature difference between ambient air and compost air,
°C

L_v = latent heat of vaporization, kJ/kg

w_a = moisture content of air, dry basis, kg/kg

w_{ak} = moisture content of compost, dry basis, kg/kg

Over a period of time θ , the total airflow can be calculated by

$$Q(\theta) = \frac{(m(\theta) - m_e)q}{\rho_a} \quad (3.9)$$

Where

$Q(\theta)$ = total airflow at time θ , m³/day

ρ_a = air density, kg/ m³

3.4.4 Modeling Airflow Based On Moisture Removal

Aeration requirements can be estimated from changes in mass and moisture over the duration of the composting process. Haug (1993) summarizes the necessary equations and approach required in estimating the quantity of air required for removing specific quantities of water during the composting process.

Based on mass and moisture balance information, the amount of water to be removed is simply

$$W = \frac{w_{ako}}{m_o} - \frac{w_{ak}(\theta)}{m(\theta)} \quad (3.10)$$

Where

W = amount of moisture removed over time θ , kg water/kg dry compost

w_{ako} = initial moisture content of compost, wet weight basis, kg

$w_{ak}(\theta)$ = moisture content of compost at time θ , wet weight basis, kg

m_o = initial dry compost mass, kg

$m(\theta)$ = dry mass of compost at time θ , kg

Haug (1993) outlines the equations needed for determining the moisture carrying capacity of the inlet and compost air. The first step is determining the actual vapor pressure of the air based on temperature and relative humidity.

Saturated vapor pressure is calculated by the Antoine equation and has the form

$$\log_{10} PVS = \frac{-2238}{T} + 8.896 \quad (3.11)$$

Where

PVS = saturation water vapor pressure, mm Hg

T = temperature of air at inlet or exit, K

The exit air is assumed to be saturated (relative humidity is 100%), therefore the actual vapor pressure (PV) equals the saturated vapor pressure (PVS) computed by equation 3.11. For the inlet air, PV can be estimated by simply multiplying the PVS by relative humidity.

The specific humidity of air is determined by

$$\omega = \frac{18.015}{28.96} \left[\frac{PV}{(PAIR - PV)} \right] \quad (3.12)$$

Where

ω = specific humidity, kg water/kg dry air

PAIR = atmospheric pressure, mm Hg

The mass of air required for removing a given quantity of moisture is calculated by

$$M = \frac{W}{(\omega_{exit} - \omega_{inlet})} \quad (3.13)$$

Where

M = mass of air required, kg dry air/kg dry compost

ω_{exit} = specific humidity of exit air, kg water/kg dry air

ω_{inlet} = specific humidity of inlet air, kg water/kg dry air

The volume of air required to remove the moisture is

$$V = \frac{M}{\rho_{ai}} [m(\theta)] \quad (3.14)$$

Where

V = volume of air, m^3

ρ_{ai} = density of air at inlet, kg/m^3

An average velocity over a given period of the composting process can be estimated by

$$v = \frac{V}{A\theta} \quad (3.15)$$

Where

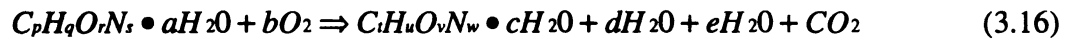
v = average velocity over time θ

A = cross sectional area of compost container, m^2

3.4.5 Modeling Aeration Based On Stoichiometric Demands

Wiley and Pierce (1955) described the aerobic composting process in terms of a complex respiration equation. The equation allows for variations in the chemical composition of different initial and final compost mixtures.

The Wiley and Pierce respiration equation has the form



Where

$C_p H_q O_r N_s \cdot a H_2O$ = organic matter

$b O_2$ = oxygen consumed

$C_t H_u O_v N_w \cdot c H_2O$ = compost

$d H_2O$ = water evaporated

$e H_2O$ = water produced

CO_2 = carbon dioxide produced

The small letters represent number of moles which changes for different conditions and materials.

Since the chemical composition of the materials composted in this study were not determined, equation 3.16 was simplified to a basic chemical expression of respiration in order to evaluate the oxygen and carbon dioxide content data collected, and has the form



The amount of oxygen needed to satisfy the stoichiometric demand of the process can be estimated based on equation 3.17 assuming that there is a 1:1 carbon to oxygen conversion ratio (Epstein 1997).

The amount of carbon in organic matter is highly variable depending on its source and can range from 0.2 to 0.6 kg of carbon in every kg of organic matter (Stevenson

1994). For this study, 0.54 kg of carbon in every kg of organic matter was used, and the amount of carbon lost can be estimated by

$$C_{lost} = 0.54[OM_o - OM(\theta)] \quad (3.18)$$

Where

C_{lost} = mass of carbon lost, kg carbon

OM_o = initial organic matter content, kg

$OM(\theta)$ = organic matter at time θ , kg

The organic matter, or volatile solids, as described by Michel et al. (1993) is

$$OM = \left(\frac{M_{dc} - M_{ac}}{M_{dc} - M_c} \right) \times 100 \quad (3.19)$$

Where

OM = organic matter content, percent

M_{dc} = mass of oven-dried compost and crucible, g

M_{ac} = mass of ash and crucible, g

M_c = mass of crucible, g

Based on data presented by Sartaj et al (1997), Lufkin et al. (1995), Michel et al. (1995), and Miller et al. (1989), naturally and passively aerated composting systems typically experience an oxygen deficit within the first few days of initial mixing and immediately following turning of the composting materials. The oxygen deficit is a result of microbial respiration during decomposition, and the reduction in carbon during this period occurs without the replenishment of oxygen (stoichiometric demand exceeds

aeration rate). In order to apply the stoichiometric model (Equation 3.17) to estimate the amount of oxygen required by microbes to consume a known quantity of carbon, oxygen cannot be replenished. Therefore, Equation 3.17 can only be applied to the reduction of carbon to the point oxygen is depleted.

Once a minimum oxygen level is reached during a process, the carbon at that time can be estimated by first estimating the mass of compost at the time using Equation 3.6. The mass can be converted to organic matter and then to carbon using Equation 3.18. The amount of carbon can be converted to equivalent moles, and using Equation 3.17, an estimate of oxygen to account for the carbon can be made and compared to the minimum oxygen level measured.

Chapter 4

Materials and Methodology

The study was conducted in the old Michigan State University Swine Facility. Hogs were present in adjacent pens of the building for most of the study and may have had some affect on ambient air conditions in the facility. However, the facility was heated during the winter.

4.1 Experimental Requirements

A passively aerated composting windrow system was the focus of this study. Although on-farm composting is typically done without enhancing aeration, passive systems afford a better opportunity to study and obtain data on parameters important in modeling a naturally aerated composting process.

Both Lynch et al. (1995) and Haug (1993) ran simulations on their respective models and reported that the airflow rates created by natural convection were lower than were measurable. The first objective of this study was to develop an apparatus fitted with proper instrumentation that would allow for the continuous measurement of physical and biological model parameters including airflow rates at very low velocities. The temperature, oxygen and/or carbon dioxide content, of the compost air at different heights, were monitored. The velocity, temperature, and oxygen content of air entering the composting media were also monitored. A complete mass and moisture balance was conducted for the fourth and final trial of the study.

4.2 Compost Experimental Design

4.2.1 Compost Chamber

The design of the apparatus used in this study and shown in figure 4.1 was designed to mimic the internal part of a compost windrow or pile.. The experimental chamber design was based on a forced aeration chamber constructed by Das et al. (1995). The principle differences in design of the experimental chamber from the Das forced aeration chamber were the lack of a blower pump at the inlet of the chamber and the top of the chamber was open to ambient air.

The composting chamber was constructed from a 1.7-m long section of 0.6-m diameter rigid plastic pipe manufactured and donated by Hancor, Inc. The base of the chamber was constructed from a piece of steel grate overlain by a plastic mesh. The grate was welded onto a steel stand 0.3 meter high. Measuring tape was mounted vertically along the chamber wall with the zero mark starting at the top of the steel grate base. The maximum depth compost could be piled in the chamber was 1.2 meter.

The measuring tape used to measure decrease in height could be read to ± 0.01 -m and translates to an accuracy of $\pm 0.003\text{-m}^3$ on a volumetric basis. Additional error must be accounted for due to the fact the surface of the compost was rarely smooth on a lateral basis and an estimate was made as to height. Most of the volume reduction occurred from settling after material was added initially or after being mixed.

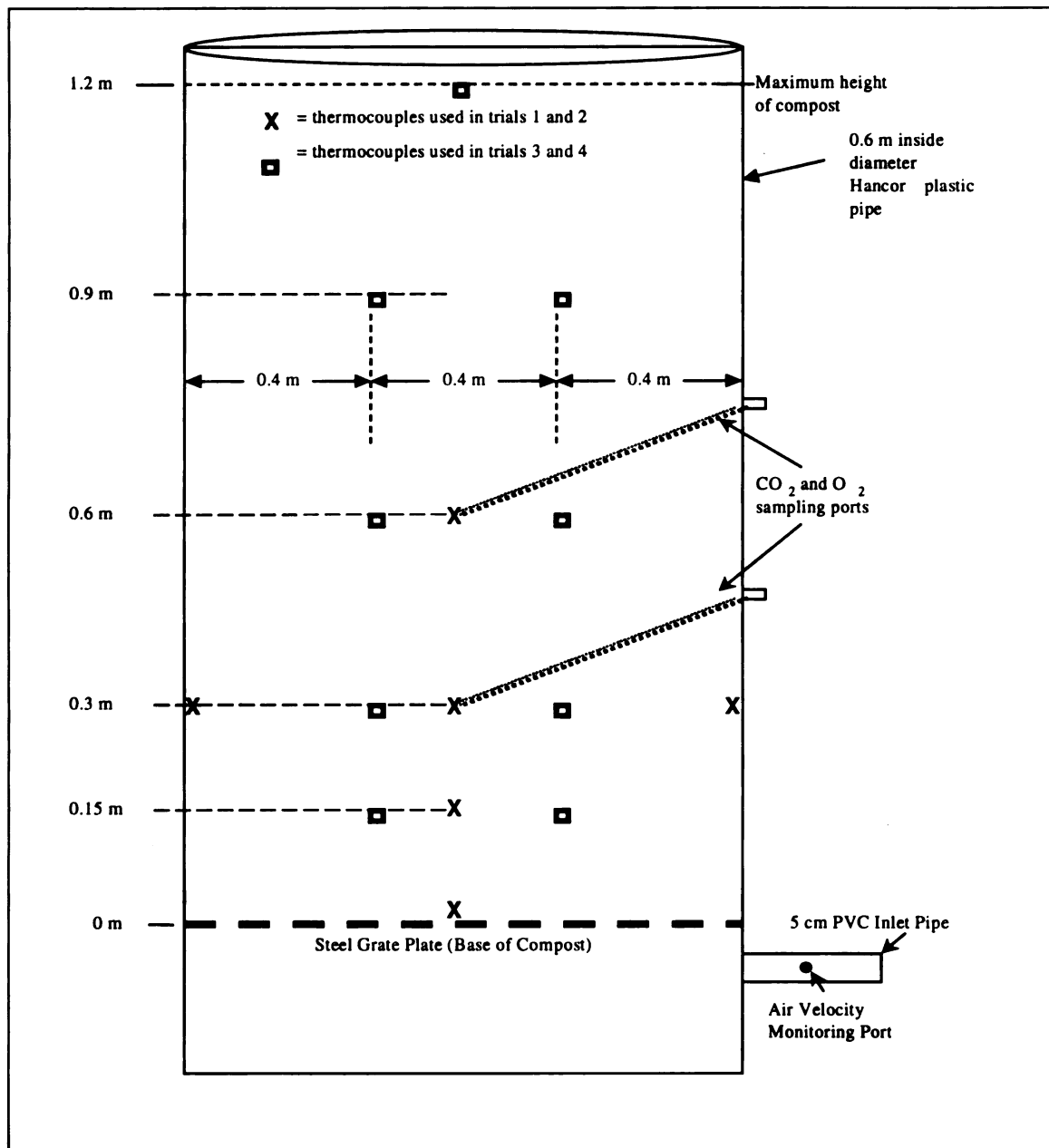


Figure 4. 1. Experimental passively aerated compost apparatus

No scientifically based recommendations could be found for sizing small-scale naturally or passively aerated composting bins or chambers. The 0.6-m diameter of the vessel was selected based primarily on availability of the material and was found to be similar in diameter to composting bins available commercially for backyard composting. The 1.2-m maximum compost height of the vessel was selected based on design recommendations for windrow heights used in dairy manure composting (Lufkin, 1996, and Rynk, 1992).

A 5-cm inside diameter PVC pipe was inserted beneath the steel grate base of the chamber to allow for ventilation of the bottom of the compost pile. The base made from the steel grate stand formed a 0.3-m deep plenum beneath the compost. The PVC pipe was fitted for a hole from which to make air velocity measurements. Two hot water heater blankets were wrapped around the chamber to insulate the chamber.

The Darcian flow based model outlined by Lynch et al. (1995) was used to design inlet pipe size for the experimental apparatus. Using the permeability given for a mixture of one volume straw, one volume cow manure, two volumes horse manure, two volume wood chips, the predicted velocity suggested that the inlet pipe should be 2.5-cm to 5-cm in diameter. The 5-cm pipe was chosen because a 2.5-cm pipe could be inserted and used instead if necessary.

4.2.2 Sensor and Probe Location

The location of the temperature type-K thermocouple sensors and gas sampling ports are shown in figure 4.1. The gas sampling ports were not inserted until trials 3 and 4. Gas samples were initially to be collected by inserting a hollow steel tube into the compost from the top down to the desired location for sampling. Concerns of disturbing the composting process by creating macropores with repeated insertions of the sampling tube led to the development of fixed gas sampling ports inserted diagonally down through the side of the chamber as shown in Figure 4.1.

The procedure for placing the 8 temperature sensors was found to be inadequate for the first 2 compost trials. The thermocouples were taped along the inside wall of the compost chamber and a length was run from the wall to the center of the compost at different heights. Settling made it difficult to assess the exact height of the thermocouple relative to the base of the compost. Two additional thermocouples had been fixed to the inner edge of the chamber at 0.3 meter off the bottom as shown in Figure 4.1. That allowed for analysis of lateral temperature distribution at the height of the compost.

The limited data collected from trials 1 and 2 were used to evaluate sensor location and led to the relocation of the temperature sensors for trials 3 and 4 to the positions shown in Figure 4.1. The lateral distribution of the thermocouples was also changed as shown in Figure 4.1, as was the manner by which the thermocouples were fed into the compost.

For trials 3 and 4, the 8 type-K thermocouples were divided into 2 sets of 4 and each set was taped together to form a strand. The end of each thermocouple was left exposed along the length of the strands. The strands were fed down into the compost from the top of the chamber. The strands were held in place by a wooden rod mounted laterally across the top of the compost chamber and fixed in place once the thermocouples were at the desired locations (figure 4.1). This prevented movement of the thermocouples as the compost settled during the process.

4.2.3 Compost Materials

For trial 1, the compost was a 4:1 dairy manure to brown leaves mixture. The dairy manure used was from tie-stall cows at the Michigan State University Dairy Farm and contained some bedding straw. This mixture was selected in spite of recommendations in Rynk (1992) in which low C:N ratios would likely result in rapid self heating of the process and the process going anaerobic in a matter of hours or days. The mixture was removed and mixed with more leaves to bring the ratio down to 2:1 for trial 2.

One of the primary objectives of the first two trials was to see if the chamber was big enough for the materials to reach and maintain optimal temperatures of 50°C to 60°C and to evaluate where to locate the temperature sensors within the composting media. Hence a mixture that was likely to heat up relatively quick was selected.

The compost produced in trials 3 and 4 was made from a 1:1 (volume basis) tie-stall dairy manure to pine wood chips mixture. The wood chips were selected as the carbon source of the mixture because they are considered an excellent bulking agent. Wood chips maintain their structure throughout the composting process, and that is beneficial for aeration. Wood chips from shredded pallets were selected because of their abundance and availability.

Raw materials composted were initially mixed in a 1 cubic yard drum before being loaded into the compost chamber. Materials were loaded into the drum based on the desired volumetric ratio of the mixture. Turning was accomplished by removing the material with a pitchfork into the drum. Materials taken from different depths were mixed thoroughly in the drums before being added back into the chamber.

In most applications of the finished compost the wood chips would have to be screened out which brings up issues of how practical such a mixture would be on a larger scale. Although pine does have a relatively fast rate of decomposition compared to other woods (Haug 1993; Rynk 1992), visual inspection of presence and to the state of wood chips remaining in the compost at the end of the composting process indicated that they did not decompose significantly. However, the objective was to find a way to measure natural airflow through a composting media and a highly porous mixture was desired.

4.3 Instrumentation

Two systems were used to collect data on temperature, velocity, oxygen gas, and carbon dioxide gas content. A Solomat MPM-4100 system was used to monitor the velocity, temperature and relative humidity of air entering the chamber, as well as the temperature of air at the surface of the compost material. A variety of probes were used with the datalogger and are described in more detail later. A CR21X datalogger was used to monitor temperature with type-K thermocouples of compost air at various locations and heights in the composting media.

An oxygen analyzer manufactured by Engineered Systems & Design, Inc. was used to measure percent oxygen content of air extracted from the composting media at different heights. A fluid analyzer manufactured by Bacharach was used to measure percent carbon dioxide content of air extracted from the composting media at different heights.

4.3.1 Solomat MPM-4100 Environmental Monitoring System

The Solomat MPM-4100 environmental monitoring system consisted of a programmable datalogger which could be hooked directly to the serial port of an IBM-compatible PC for downloading data as well as for programming the datalogger itself using software provided with the Solomat system. A variety of sensors and probes were used with the Solomat MPM-4100 system.

A Solomat 129MSX hot-wire anemometer was used to measure the air velocity entering the compost chamber. The probe has a range of 0.10 to 12.00 m/s with a

repeatability error of ± 0.01 m/s, and was factory calibrated every 6 months of use. The factory reported no deviation in calibration during the entire period of the study. The datalogger was capable of making 2.5 velocity readings every second and was programmed to average and write data to a file every hour.

A smoke gun was used to visually check for air flow into the inlet pipe when it was detected in trial 3 after the first turn and also in trial 4. The hot-wire anemometer was removed when the gun was used to prevent exposure of the sensitive instrument to smoke.

A Solomat 355RHX relative humidity probe was used to measure both temperature and relative humidity of the air entering the composting chamber. The probe made relative humidity measurements with a polymer capacitor and a Pt100 platinum electrode and had a range of 0 to 100% although the specifications stated there was a potential for higher error at a relative humidity above 75%. The probe was placed in the top 10 cm of the compost during trial 1 but condensation formed on the probe and resulted in mostly erroneous readings. The probe was being serviced during trial 2 and was not used again until trial 3.

The 355RHX probe was factory calibrated once a year and a kit provided by the factory allowed for monthly calibration checks. No deviations were reported until condensation on the polymer capacitor damaged the probe during the final trial run. The relative humidity probe made 1.5 relative humidity and temperature readings per second, and the readings were averaged and recorded on a hourly basis.

The Solomat Pt100 platinum temperature sensor built in and used with the Solomat 355RHX relative humidity probe was calibrated at the factory at had a reported error of $\pm 0.1^{\circ}\text{C}$. No deviations from the original calibration was reported even though the humidity probe was damaged by extended exposure to condensation when it was placed within the compost. The probe was placed at base of the inlet for trials 3 and 4 after being repaired.

A Solomat type-K (copper constantan) thermocouple was used to measure the ambient air temperature during trial 1 and was moved to the compost surface for trials 3 and 4. The thermocouple had a range of -80°C to 1260°C with a repeatability error of $\pm 0.2^{\circ}\text{C}$. The datalogger made 2.5 temperature readings per second, and the readings were averaged and recorded on a hourly basis.

The Solomat MPM-4100 kit also included the 1201GSX carbon dioxide sensor which had a range of 0 to 5000ppm (0 to 0.5% atmospheric). This range proved to be too low for the probe when placed at the base of the compost pile. The carbon dioxide probe was not used after the 1st trial as sporadic and extreme fluctuations in readings of ambient air indicated the probe likely suffered damage from the continuous exposure to the high concentrations of carbon dioxide gas in the compost air.

4.3.2 Campbell Scientific CR-21X datalogger

The 8 type-K thermocouples used to measure air in the compost at various locations were connected to a Campbell Scientific CR-21X datalogger. The datalogger also provided a reference temperature measured at the panel. Ambient air temperature was monitored using a panel measurement made by the datalogger. This temperature was frequently checked against a mercury thermometer placed nearby.

The CR21X recorded and converted voltages measured by the thermocouples into temperatures. The type-K thermocouples used with the datalogger had a sensitivity of $\pm 0.5^{\circ}\text{C}$. The factory set calibration value in the datalogger for the thermocouple was checked against measurements made with a mercury thermometer at ambient air conditions, in an ice water bath, and in a heated laboratory oven. No deviations beyond the sensitivity of the probes were observed. Therefore, no changes were made to the factory calibrations of either datalogger.

The datalogger was programmed to take a reading every 5 seconds and average and record the readings at specified intervals. For the initial trial composting run, an average was computed every 15 minutes but was changed to every half hour then again to every hour as the rate of change in temperature was found not to be significant enough in to warrant the collection of so many data points. For trials 3 and 4, temperature readings were averaged every 3 hours.

4.3.3 Oxygen and Carbon Dioxide Gas Analysis

Gas samples analyzed for both carbon dioxide and oxygen were collected by manually pumping an aspirator bulb and extracting compost air through the sampling tubes shown in Figure 4.1. The Bacharach system recommended pumping the aspirator 18 times while trial and error with the oxygen sensor found that readings usually leveled off after 10 pumps and 15 pumps was used as protocol. Because of concern of removing too much air during the composting process based on findings by Ferns (1987), gas sampling was limited mainly to the oxygen sensor while carbon dioxide was sampled whenever the oxygen content changed substantially from the previous reading.

The atmospheric content of oxygen and carbon dioxide gas in air with no water vapor is 20.95% and 0.03%, respectively (Eagleman 1985). Oxygen content often varied $\pm 1\%$ of the standard level and may have been a result of the enclosed environment where there was respiration from hogs. The Bacharach analyzer did not detect carbon dioxide gas in ambient air because it was not sensitive enough to record such low concentrations. But when compost samples were taken and both gases were detected, the sum of both gas contents was always reasonably close to the sum of the standard atmospheric content of both gases (20.98%).

The Bacharach carbon dioxide gas sampling kit utilizes a reagent fluid called Fyrite stored in a calibrated vessel. Gas is sampled from the composting media and pumped into the vessel with the aspirator bulb. The active ingredient in Fyrite, potassium hydroxide, absorbs carbon dioxide out of the sampled gas. The absorption results in the

expansion of the fluid into a burette with a range of 0% to 20%, with an accuracy of $\pm 0.5\%$.

The Engineered Systems and Design Model 630 oxygen gas sampling sensor utilizes a digital meter that measures and converts an electrode reading. The electrode was fitted into a PVC chamber adapted to fit the same sampling tube used with the Bacharach sampling kit. The sensor had a range of 0% to 100% with $\pm 0.1\%$ sensitivity.

Gas samples of the compost air were extracted and monitored for oxygen on a daily basis following initial mixing and whenever the compost was turned. As soon as oxygen concentrations showed any trend of leveling off, typically at 15% to 20%, the sampling frequency was reduced to every 2-3 days in order to minimize the amount of air removed from the relatively small mass of composting media. There was concern based on research conducted by Ferns (1987) from removing carbon dioxide through gas sampling could potentially benefit the aerobic microbes in a way that would not occur with a full scale system.

Oxygen was selected as the gas to sample periodically based on the easy and accuracy of obtaining a measurement. The Bacharach CO₂ gas sampling kit utilized a very caustic material that required careful handling and also had a lower level of accuracy because it depended on eyeing a fluid level. The O₂ apparatus utilized a digital meter and sensor that was more accurate and also did not pose any health hazard.

4.4 Compost Moisture Content

Samples taken of the initial compost mixture from all trials and from different depths when the compost was turned were analyzed for moisture content on a wet weight basis using methods described by Rynk (1992).

Moisture contents were measured on triplicate compost subsamples of the initial mixture of raw materials. The materials were mixed in a large drum before being added to the chamber. Small portions of the material were taken from each batch mixed in the drum. The composite sample was divided into the triplicate subsamples used in determining moisture content.

Compost was removed from the chamber for turning and when a trial was over. Material was removed at specific height intervals (0.3m to 0.6m) using a pitchfork and/or shovel and loaded into the same large drum used for the initial mixing of the raw materials. A sample was taken from the drum for each section of compost removed to measure moisture content.

The wet compost samples were placed in steel pie plates and weighed using an Ohaus laboratory scale accurate to ± 0.01 g. The pie plates with the wet compost samples were dried in a laboratory oven at 102°C for 48 hours. The samples were removed, allowed to cool, and weighed. The steel plates were weighed before the wet compost samples were added and after the dried samples were removed.

The moisture content (wet basis) is calculated by:

$$MC_{wb} = \left[\frac{(M_{wc} - M_{dc})}{(M_{dc} - M_c)} \right] \times 100 \quad (4.1)$$

Where

MC_{wb} = moisture content, wet basis, percent

M_{wc} = mass of wet compost and container (pie plate), g

M_{dc} = mass of dry compost and container (pie plate), g

M_c = mass of container (pie plate), g

4.5 Compost Organic Matter Content

Organic matter content was measured in samples taken of the initial compost mixtures and on samples taken after the composting process had ceased for trials 3 and 4. The organic matter, or volatile solids, of the samples was determined using methods described by Michel et al. (1993).

Compost samples were placed in ceramic crucibles and weighed. The samples were then dried in an oven at $102^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 48 hours and reweighed. The dried samples were burned at 550°C in a furnace until all material was white ash (2-3 hours). The crucible and ash samples were removed, allowed to cool, and weighed. A Precision Scientific oven was used to dry the samples, a K.H. Huppert electric furnace capable of reaching 1000°C was used to burn the samples, and an Ohaus analytical scale accurate to $\pm 0.0001\text{g}$ were used in this procedure.

4.6 Compost Mass and Moisture Balance

A compost mass balance was conducted on the materials composted in trial 4. Based on the methodology to obtain moisture contents described in section 4.4, each batch of materials mixed in the large bin prior to being added to the composting chamber were weighed using an Ohaus scale capable of measuring up to 50kg with a sensitivity of $\pm 0.1\text{kg}$. These are the same batches from which material was taken for moisture content measurements and together this information was used to develop a mass and moisture balance of the entire trial 4 composting process.

This same procedure was used when the compost was unpacked for turning and when trial 4 was over. An additional measurement of compost mass and moisture content was made one year after the trial had ceased. The information collected from the mass and moisture balance was important for determining the rate of disappearance of dry matter or decomposition rate (k) from Equation 3.5. The value k was used in equation 3.6 to estimate the volumetric airflow rate required in order to maintain a constant process temperature (Keener et al. 1993).

A complete mass balance was conducted during trial 4 in order to evaluate the decomposition rate of the composting material and total mass of water removed. Knowledge of both these parameters were required for the different models applied to this compost process and system. As stated previously, the moisture content of the compost material at turning was taken from the in-situ permeability core and was used to estimate mass of water at each layer.

4.7 Compost Permeability Measurement

The compost permeability factor (K) of hand packed cores (trial 3) and one in-situ core (trial 4) was measured based on the method described by Lynch et al. (1995). The apparatus and instrumentation layout used to obtain K are shown in figure 4.2. The chamber was packed to a length of 28.5 cm for K measurements made on material from trial 3. Retaining plates shown in figure 4.2 were added for trial 4 and reduced the length the compost was packed to 20.3 cm.

To measure permeability, a sample of the compost used in trial 3 was removed from the top 5-cm of the chamber prior to turning. A known amount of material was packed into a 20-cm diameter core. Additional amounts were added in order to obtain a permeability for different bulk densities. The methodology used was checked for accuracy by making measurements on 2 cores packed to the same bulk density and yielded identical results.

The core used in trial 3 was adapted for in-situ use in trial 4. The core was removed when the trial 4 compost was turned, and weighed on the 50-kg scale before permeability measurements were made. The material was then removed from the core, mixed, and a subsample was taken to measure moisture content. This moisture content was subsequently used as the moisture content of the entire compost mixture at turning.

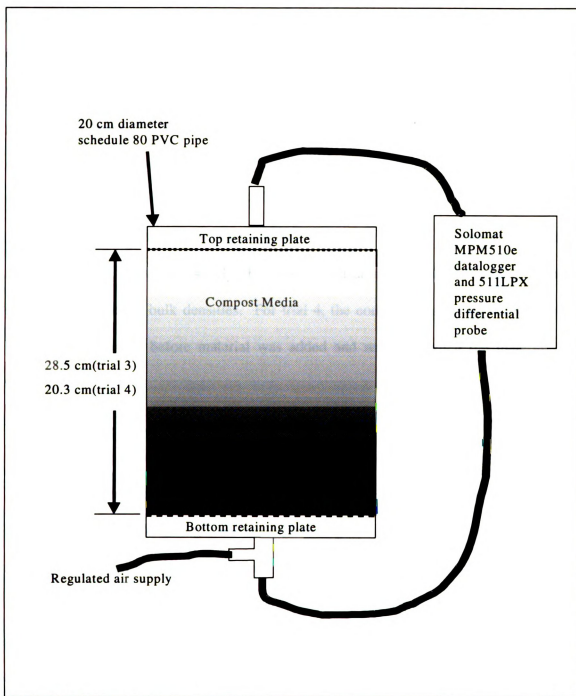


Figure 4.2. Compost permeability apparatus

Air was supplied and regulated using a laboratory pressurized air source. A Gilmont bubble air flow meter was used to measure the airflow rate entering the permeability core. A Solomat MPM510e datalogger and a 511LPX differential pressure probe with a range of ± 7000 Pa and a ± 0.3 Pa resolution was used to measure the pressure drop across the length of the permeability core.

Permeability measurements were made on the 1:1 dairy manure to wood chip mixtures used in trials 3 and 4 only. For trial 3, measurements were made on cores hand packed to 3 different bulk densities. For trial 4, the core was placed on the steel plate base of the chamber before material was added and removed when the material was turned.

Retaining plates were added to top and bottom of the permeability core in trial 4. This aided in minimizing disturbance of the material in the core during transport from the swine facility to the MSU Agricultural Engineering Soil and Water laboratory where K measurements were conducted. The top 2-cm of compost in the permeability core was scraped off following removal of the core from the compost chamber. This helped provide a smooth and relatively even surface for fitting the top retaining plate before transport.

4.9 Predicting Velocity

In order to better interpret and understand the temperature, gas content, and air velocity data collected, several models were used to predicted air flow rates and

requirements based on physical, biological, and chemical properties of the composting process.

Passively aerated composting is not a steady-state process. But short periods of the process were observed to be at relative steady states based on temperature data collected in the experiment. This allowed for comparison between measured and predicted instantaneous airflow based on mass and moisture changes throughout the process, and the temperature maintained during the brief steady state period observed.

4.9.1 Darcian Flow Based Model

The Darcian flow equations used by Lynch et al. (1995) modeled lateral and vertical flow through a porous media for a passively aerated composting windrow system. For the compost chamber used in this study, flow into the compost chamber was assumed to occur vertically upward because the side walls of the chamber would have prevented any significant lateral movement. This simplified the problem and combining Equations 3.1 and 3.2 resulted in an air velocity prediction equation applicable to this study and has the form

$$v = - \frac{K(\rho_b - \rho)g}{\mu} \quad (4.3)$$

One of the first problems with using this model was the lack of any information on what the bulk densities were of compost permeabilities reported by Lynch et al. (1995). For trial 3, permeability measurements were made on cores packed to 3 different bulk densities. But the most accurate way of getting permeability would be to obtain *in-*

situ cores on which to conduct measurements on. That was accomplished in trial 4. Permeability measurements made on both the packed and *in-situ* cores were based on methods used by Lynch et al. (1995).

The density of air entering the chamber was estimated using the Ideal Gas Law (Equation 3.3). The density of compost air was estimated using the Ideal Gas Law. Air velocities were predicted and different assumptions were made of compost air vapor content and gas composition in order to analyze their potential effect on airflow. The assumptions made in predicting air velocity using Darcy's Law were:

- 1) The compost air was assumed to be dry and the oxygen and carbon dioxide contents were assumed to be at standard atmospheric levels,
- 2) The compost air was assumed to be dry and the density was adjusted based on measured temperature and oxygen contents, and
- 3) The compost air was assumed to be at saturation and the density was adjusted to measured temperature and oxygen contents.

Assuming the compost air to be dry allowed for application of Darcy's Law to predict air velocities using just inlet and compost air temperature data. Research cited by Bach et al. (1987) found that air leaving compost piles is saturated when compost moisture contents are above 50% (wet weight basis), but airflow is responsible for

cooling heated air resulting in saturation. Therefore, without airflow, compost air may not necessarily be saturated.

The compost air densities were determined at the layer of compost with the highest temperature throughout the process (0.6 m). The temperature data was used to estimate densities and develop predicted velocity curves for trials 3 and 4 based on the assumptions listed above.

4.9.2 Process Kinetics Based Model

The equations developed and used by Keener et al. (1993) to predict air flow rates required to maintain process temperatures in forced aerated systems were applied to the passively aerated composting system used in this study. These equations are based on process kinetics and are the same for both a forced and naturally aerated composting process.

Mass balance data collected in trial 4 was used to derive a decomposition rate, k , using equation 3.4. The k determined in trial 4 was used with the trial 3 data in predicting air velocities for both trials based on maintaining a specific temperature using equation 3.5 and 3.6.

The heat of combustion, h_c , used in equation 4.5, was not available for the dairy manure and wood chip mixture used in the study. Published values of h_c summarized in Keener et al. (1993) ranged from 19.0 MJ/kg to 24.7 MJ/kg for various materials. A

value of 23 MJ/kg was used and based on the range of values reported for active materials such as sludge (24.7 MJ/kg) as opposed to less active materials such as leaves (22 MJ/kg).

The humidity probe failed during trial 4 and an ambient air relative humidity of 50% was used which was the approximate average observed during trial 3. Keener et al. (1993) assumed the air exiting is saturated and that the temperature at the exit was the design process temperature. These conditions did not appear to exist during any of the trials. Therefore, the layer with the most frequently observed maximum temperature during the process was used and the air at that layer was assumed to be at saturation.

Saturated air has been reported to occur in the compost just above the layer of maximum temperature (Miller et al. 1989). This was based on the observation that the compost was significantly wetter above the zone of maximum temperature. A similar zone was also visually observed when unpacking the compost chamber for turning or when the process was complete.

Predicted air velocities were computed based on the overall maximum temperature measured during the composting and based on the compost surface temperature. Keener et al. (1993) tabulated most of the thermodynamic properties of air used in equations 3.5 and 3.6.

A process kinetics model was used for comparison against measured air velocities at temperatures selected from regions where the process was occurring at a relative steady state (compost temperature relatively steady). The predicted velocity represents the airflow required to maintain a specific temperature during the process in order to decompose the materials.

4.9.3 Moisture Removal Based Model

The moisture balance conducted in trial 4 allowed for the estimation of airflow required to account for the moisture removed during the composting process. Haug (1993) summarized the equations required to determine the water carrying capacity of the air entering and leaving the composting process.

Data from trial 4 was used to evaluate the predicted air velocity required to remove a known amount of water. Relative humidity of the inlet and exit air was assumed to be 0% and 100%, respectively, for the same reasons described in section 4.9.2.

Predicted air velocities were computed using the same temperature data points used in the process temperature and kinetics based predictions of air velocities. The predicted values were compared to the actual air velocities measured same time the temperature data used in the air velocity predictions was measured.

4.10 Predicting Oxygen and Carbon Dioxide Content and Aeration Requirement Based On A Simplified Stoichiometric Respiration Model

A stoichiometric estimation of oxygen consumed and carbon dioxide released based on a known amount of carbon was made using equation 3.15 and compared to the measured oxygen and carbon dioxide content of trial 4. The amount of carbon consumed was computed using equation 3.16.

In order to predict the amount of oxygen required by microbes for decomposing a given amount of carbon, predictions were made when the lowest oxygen content was measured. That was when the stoichiometric oxygen demand of the microbes was most likely greater than the rate oxygen was replenished by aeration through the compost. The carbon was estimated from the organic matter content. Since organic matter content was measured on samples taken initially and when the process had ceased, the decomposition rate (k) determined from the loss in compost mass was used to estimate organic matter content at the time when the lowest oxygen content was measured.

CHAPTER 5

EXPERIMENTAL RESULTS

5.1 General Observations

Probe design and placement was experimental for trials 1 and 2, and changes made for trials 3 and 4 were generally successful. Placing the temperature thermocouples and gas sampling tubes in the composting media so that they did not change in height significantly during composting was the primary concern. The relatively small volume of the chamber also led to concern that inserting and removing probes would disturb the mixture in terms of aeration and airflow. These factors led to fixing the temperature and gas probes for trials 3 and 4.

There was concern over the effect the repeated extraction of compost air for sampling carbon dioxide and oxygen gas content would have on the overall compost process. Removing carbon dioxide evolved from microbial respiration could potentially benefit the aerobic microbes compared to if the gas was left. Therefore, only oxygen gas was regularly measured.

Another factor of concern during the study was that the chamber was adjacent to a set of loading area doors that were not well insulated, and within 2 meters of a ceiling heater vent. The composting chamber was open at the top to ambient air and any draft especially of significantly warmer air could have an impact on the natural convective aeration mechanism of the composting process.

5.2 Measured Data

Table 5.1 summarizes the information and data collected and reported for each composting trial. The raw data collected from trials 1, 3, and 4 is presented in Appendix A. For trial 3, after the material was turned, and trial 4, only the temperature and oxygen data collected and used in modeling is presented in the following sections.

5.2.1 Composting Trial Run 1

The objective of the first trial was to observe and evaluate the performance of the overall experimental apparatus. A high nitrogen mixture was used in the initial runs with the objective of creating a process that heated up quickly so that uncertainties with the probe locations, sampling protocols, and the compost chamber itself could first be addressed in relatively rapid manner.

The temperature trends shown in Figure 5.1 indicated the vessel was capable of sustaining a composting process. The process reached temperatures above 70 °C within two days indicating the chamber was of sufficient size to sustain composting. Although no carbon dioxide or oxygen content measurements were made, the composting process was producing very offensive odors after the second day. The trial was immediately ceased and the mixture unpacked from the chamber. The trial 1 temperature thermocouples placed above 0.3-m height settled substantially. One thermocouple were stretched and damaged leading to a change in the method of thermocouple placement for trials 3 and 4.

Table 5.1. Summary of information and data collected during study

Trial no.	Dates data recorded	Mixture used	No. turns	Parameters monitored
1	9/13/96 - 9/16/96	4:1 leaves to manure	0	Ambient air and compost temperature, inlet air velocity, moisture content
2	9/19/96	2:1 leaves to manure*	0	None
3	9/30/96 - 12/4/96	1:1 wood chips to manure	1 (10/15 /96)	Height, ambient air and compost temperature, inlet relative humidity and air velocity, compost carbon dioxide and oxygen content, moisture content
4	2/25/97 - 4/19/97	1:1 wood chips to manure	0	Height, ambient air and compost temperature, inlet relative humidity and air velocity, compost carbon dioxide and oxygen content, moisture content, mass, organic matter

* trial 2 mixture made from mixing more leaves to trial 1 mixture

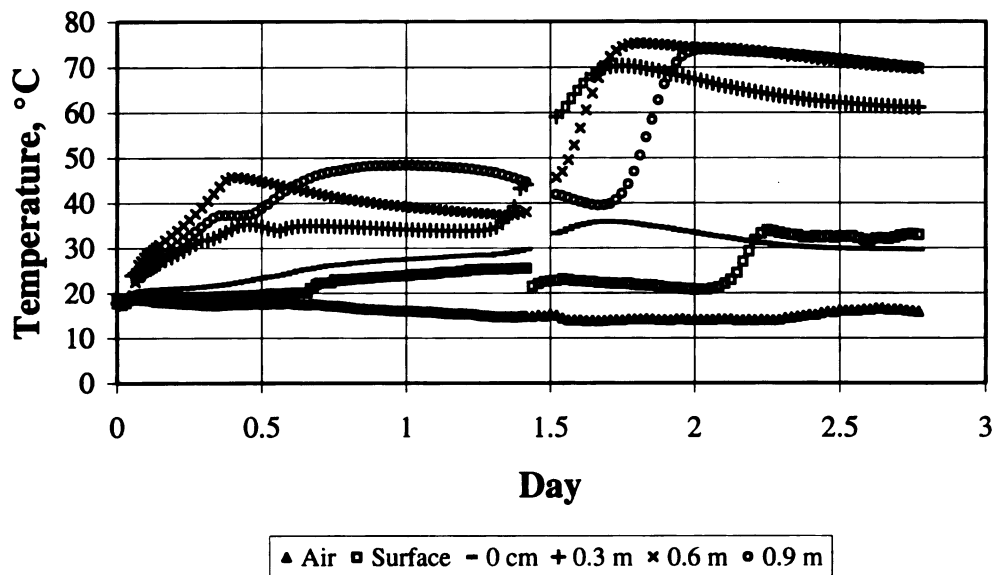


Figure 5.1: Compost Trial 1 Temperature Data (4:1 Dairy Manure to Leaf Mix)

A series of temperature readings were taken at 0.3-m above the base of the compost in order to determine lateral distribution. This was accomplished by strategically placing a total of three thermocouples at that layer: one at the center, and 2 located opposite of each other at the wall of the chamber. Referring to Figure 5.2, the edges were substantially lower in temperature than the center of the compost, and this was due to the chamber not being insulated.

The lateral temperature difference between the center and edge temperatures was reduced some by adding the hot water heater insulation blanket, but for following trials, a second insulation blanket was added in addition to the first in order to further minimize heat loss through the outside wall of the chamber. It was concluded the best setup for

temperature measurements at 4 heights (0.15-m, 0.3-m, 0.6-m, and 0.9-m), and at 2 strategic lateral locations in each height to provide a means of checking lateral temperature uniformity.

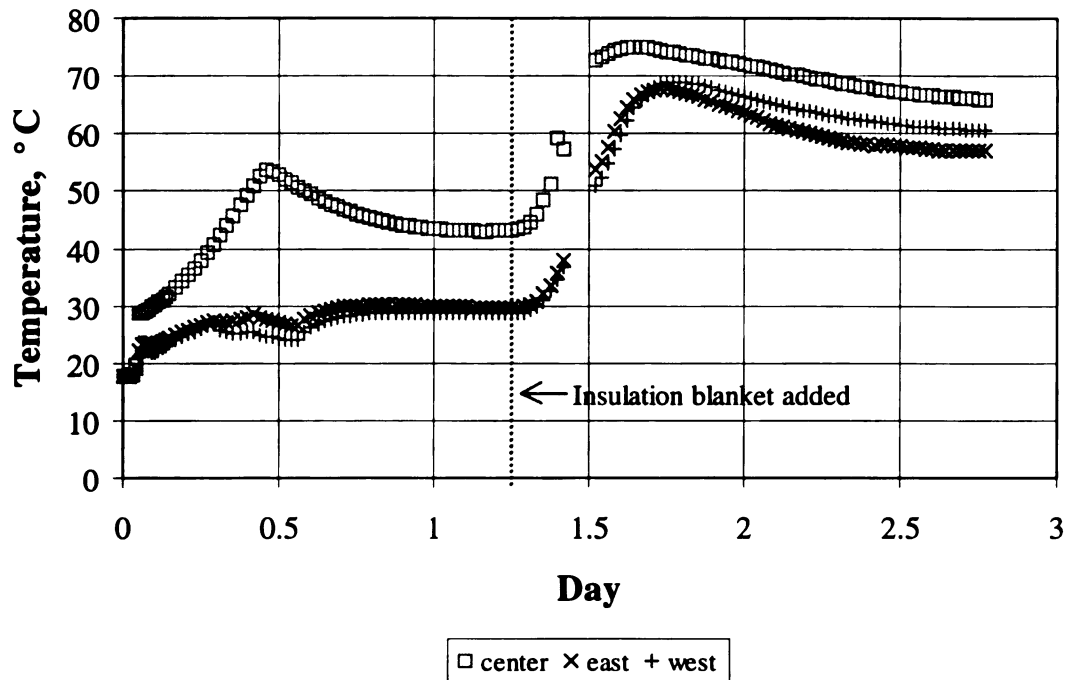


Figure 5.2: Compost Trial 1 Lateral Temperature Distribution (0.3-m height)

The 355RHX humidity probe was placed in the top layer of the compost for the 1st trial, but the high moisture of the compost damaged the polymer capacitor used to determine relative humidity and the probe was removed from within the compost and placed on top of the compost column. The platinum temperature sensor was still functional, so the surface temperature data was retained for analysis.

The wet weight basis moisture content of the initial mixture and of the mixture sampled after it was unpacked 3 days later (“Final” mixture) are summarized in Table

5.2. Although the 1st trial was terminated within 3 days of initial mixing, the moisture content (wet weight basis) decreased 11.3%. The moisture was likely lost from rapid evaporation caused by the high temperatures (in excess of 70 °C) which were observed by day 2 (Haug, 1993). There was a 33-cm drop in the compost height.

Table 5.2: Initial and “Final” Moisture Content of Compost – Trial 1.

Height, cm	Initial Moisture Content, percent (9/13/96)	Height, cm	Final Moisture Content, percent (9/16/96)
0-41	57.3	0-30	44.0
41-81	55.8	30-61	46.0
81-122	59.6	61-89	49.0
Average	57.6	Average	46.3

5.2.2 Composting Trial Run 3 – Initial Stage

The 3rd trial run was conducted on a 1:1 mixture of dairy manure and pine wood chips. The mixture was selected based on the general information Lynch et al. (1996) published on mixtures used in passively aerated composting systems. Less wood chips were used than typically recommended in other literature (Epstein 1997; Haug 1993; Rynk 1992).

The intent of using less than recommended wood chips was to provide enough of a bulking agent while not supplying too much available carbon. Decomposition of the dairy manure would have to liberate enough heat to bring process temperatures up into the optimal 55-60 °C range. This was the temperature range predicted to generate a measurable airflow.

Ambient temperature, oxygen content, and relative humidity data are plotted in Figure 5.3. The relative humidity in the facility varied greatly throughout the day and almost directly with the temperature of the outside air. The heat was turned on during the 3rd day of the trial likely drying the air out even more. The oxygen did fluctuate at most by slightly over 1%. There were no pigs present during this period and the changes in ambient room oxygen did not seem to correlate with the ambient room temperature. The source of the fluctuation could be sensor drift. Without air conditioning or humidifiers/dehumidifiers, controlling relative humidity was impossible.

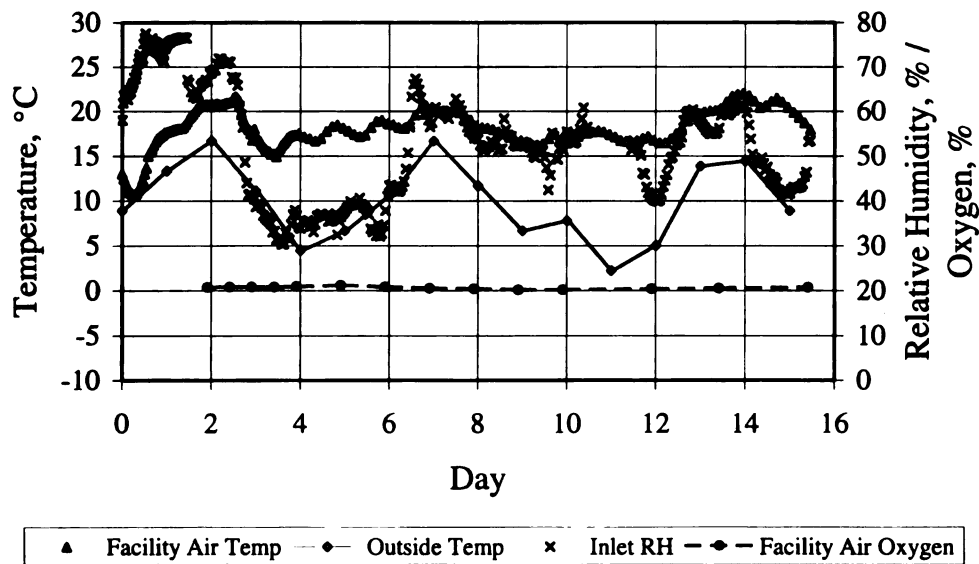


Figure 5.3: Ambient Temperature, Oxygen Content and Relative Humidity Measurements – Trial 3, Initial Phase.

Based on the literature available to date, the first direct measurement of airflow through a naturally aerated composting process is shown in Figure 5.4. But the lack of

many data points did raise concern that it may have been an anomaly independent of the composting process, such as disturbances from human activity.

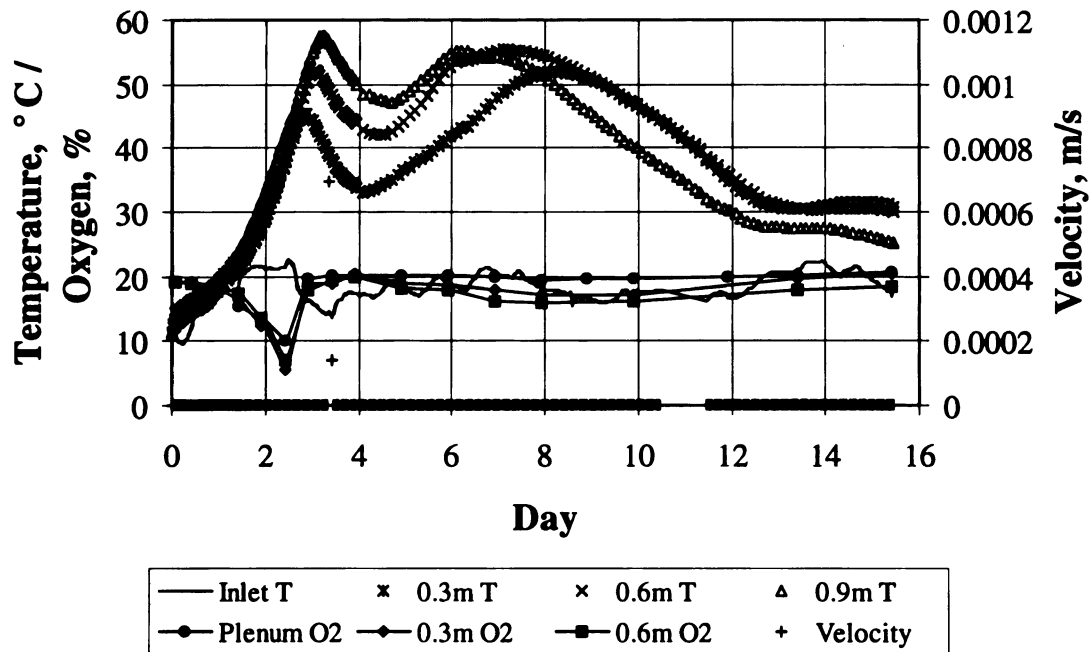


Figure 5.4: Compost Temperature, Oxygen, and Inlet Air Velocity Measurements – Trial 3, Initial Phase

The measured velocities occurred within an hour of the observed peak temperature and the temperature differential between ambient air and compost air could have driven the movement of air (convection). The temperature in the pile decreased immediately after peaking, and it was concluded based on physical observation of the material that the compost moisture content dropped below that needed to maintain the process.

Oxygen contents shown in Figure 5.4 immediately decreased as compost temperature increased. The oxygen content at 0.3-m reached 5%, the critical level below which anaerobic activity begins to become a factor. But as quickly as the content decreased there was an immediate increase the following measurement to levels slightly higher than those measured at the start of the process as shown in Figure 5.4.

The sudden increase in oxygen occurred just prior to the first measured air velocity. The increase in O₂ content was more rapid than the rate of the initial decrease which suggest that some degree of air flow must have occurred and that the measured air velocity may be accurate.

The moisture contents of samples collected the initial mixture and when the mixture was turned are summarized in Table 5.3. The compost of trial run 3 was turned after the 15th day by extracting approximately 25-30 cm of material at a time using a shovel and pitchfork. The initial moisture content was too low and would explain why the process appeared to peak and suddenly slow as shown in Figure 5.4.

Water was added to the compost from the top using a commercially available soaker hose. Temperatures immediately rose. Unfortunately, to avoid disturbing the composting media, there was no means of measuring moisture content of the compost after the water was added.

Table 5.3: Moisture Content of Initial Compost Mixture and Following Turning– Trial 3

Height, cm	Initial Moisture Content, percent (9/30/96)	Height, cm	Moisture Content of Turned Compost, percent (10/16/96)
0-41	42.9	0-41	35.6
41-81	39.8	41-61	32.6
81-122	44.4	61-91	41.3
		91-105	41.0
Average	42.4	Average	37.6

Carbon Dioxide and oxygen contents were summed and are shown in Figure 5.5. The sum was taken in order to make comparisons against the standard air content of the sum of the two gases which is 20.98% (Eagleman 1985). The minimum sum observed was 19% and the maximum was 22%. Sources of deviation from the standard content could be from animal respiration or more likely from the fact that not all oxygen used in microbial respiration is converted to carbon dioxide (Atlas et al. 1981).

The rate of volume decrease was compared with temperature at the 0.6-m height (maximum process temperature) in Figure 5.6. The volume was reduced by approximately 0.05 m³ in less than 16 days. A majority of reduction occurred from the beginning up until the temperature peaked on day 3 at 52 °C. The reduction during this period was likely due more to the initial settling of material than to microbial activity. Volume reduction later in the process was due primarily from microbial activity.

When the process slowed and temperature decreased the volume leveled off as Figure 5.6 shows. As soon as temperatures increased following the addition of water, the volume decreased but at a slower rate. As soon as the temperatures started declining again, the volume once again leveled off.

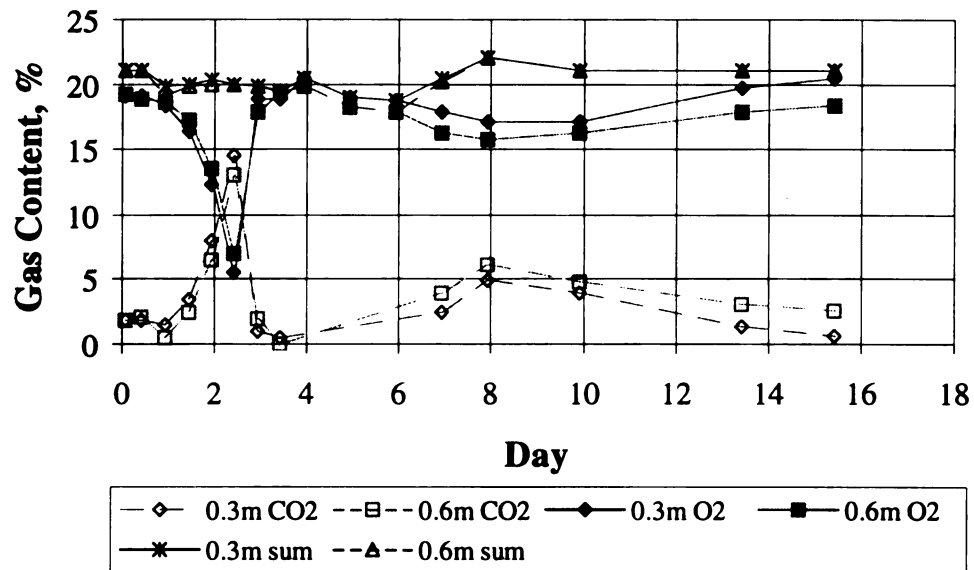


Figure 5.5: Oxygen and Carbon Dioxide Measurements – Trial 3, Initial Phase

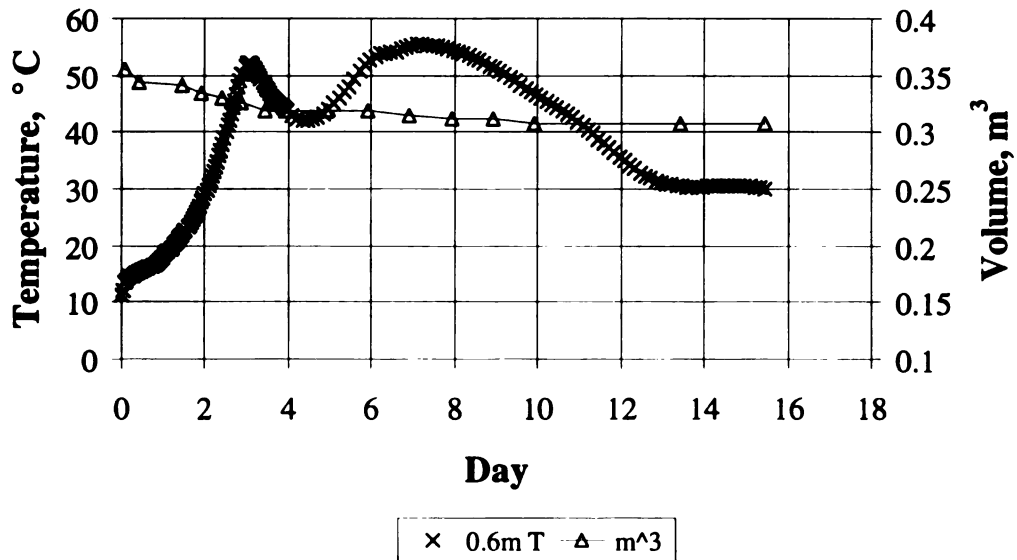


Figure 5.6: Volume of Compost – Trial 3, Initial Phase

5.2.3 Composting Trial Run 3 – After 1 Turn

The compost mixture was observed to be dry following extraction from the chamber. Each layer extracted was sub-sampled for moisture content measurements and then the layers were mixed with each other. Water was added to the compost during mixing and then the compost was divided into three large drums. A sample was taken from each drum for moisture content measurements before being dumped into the chamber.

The moisture contents of the compost after water was added and when the composting trial run had ended are summarized in Table 5.4. The top layers (30-61 cm and 61-102 cm) had more water added than the bottom layer (0-30 cm) so that any excess water would infiltrate down and contribute to the moisture of the lower layer. As can be seen at the end of the trial run, the moisture contents in the top 2 layers decreased while the bottom layer increased by the end of the process.

Table 5.4. Moisture Content of Initial and Final Compost Mixture– Trial 3, After 1 Turn.

Height, cm	Initial Moisture Content (After Adding Water to Compost), percent (10/16/96)	Height, cm	Final Moisture Content, percent (12/5/96)
0-30	62.4	0-30	65.4
30-61	69.3	30-61	66.4
61-102	70.0	61-79	51.8
Average	67.2	Average	61.2

Ambient temperature, oxygen, and relative humidity data are plotted in Figure 5.7. As with the initial stage of trial 3, the relative humidity in the facility varied greatly throughout the day but did not respond with the outside temperature as directly for part of

the trial. Several pigs were brought into the facility starting on the 22nd day which is when the trends between relative humidity and outside temperature began differing. Respiration of the pigs may have added moisture to the air and reduced the affect outside air was having on the relative humidity in the building. The ambient O₂ content ranged from 20.3 to 21.8 percent and variations did not correlate with changes in air temperature and relative humidity.

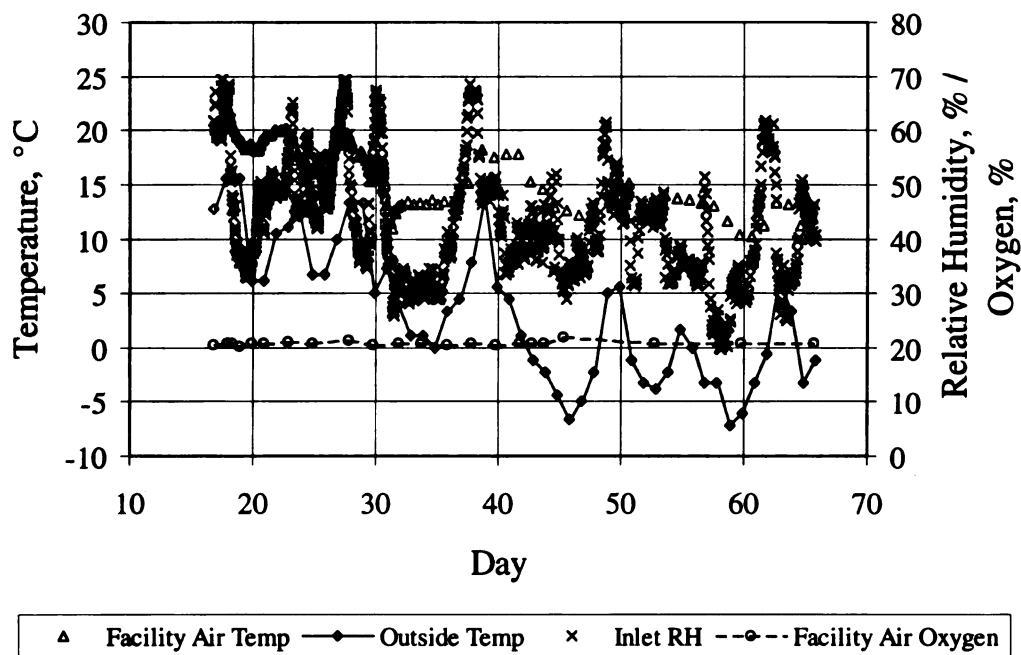


Figure 5.7. Ambient Temperature and Relative Humidity Measurements – Trial 3, After 1 Turn.

The temperature and oxygen measured in the inlet and 0.6-m layers, and the air velocity entering the composting chamber are plotted in Figure 5.8. As with the initial stage of trial 3, the temperature of the compost increased immediately and reached near

maximum temperature within the same period of just less than 4 days. But significant airflow was detected for a much more extended period of time than during the initial stage and before maximum temperatures were reached. The temperatures also were maintained at or near the optimum range of 55-60 °C during the same period air velocity was detected.

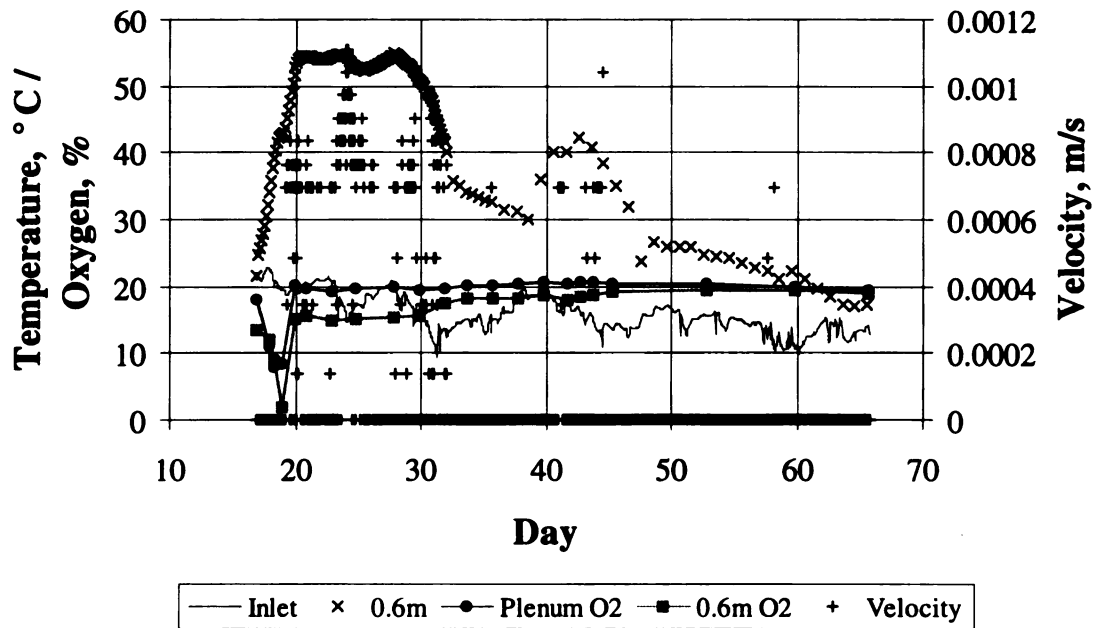


Figure 5.8: Temperature, Oxygen, and Air Velocity Measurements – Trial 3, After 1 Turn.

The air velocity varied extensively throughout the period it was being detected. The smoke gun was used for observation purposes when airflow was being measured and also when it was not. The smoke gun clearly indicated flow into the inlet pipe when airflow was being measured. On two occasions early in the process when airflow was not

being detected the smoke gun indicated there was flow coming out of the inlet pipe possibly due to a carbon dioxide which is a denser gas than oxygen.

The oxygen content at 0.6-m height reached a minimum of 2% within the first 2 days of the process. This was also when the smoke gun indicated for the first time flow coming out of the inlet. The low oxygen contents indicated that high carbon dioxide contents could be the source of the back flow observed with the smoke gun. However, several other checks with the smoke gun when no airflow was being measured did not indicate further back flow.

A slight plateau in the temperature profile during the initial increase was observed. It was at this plateau that oxygen contents were at their lowest levels, and airflow was detected just after temperatures began increasing again. This is possibly some type of breakthrough not found or reported in scientific publications and is yet another phenomena worthy of further study.

The oxygen deficit observed early in the process began recovering as soon as airflow was detected. The air velocity was measured for a considerable period of the composting process. Both heights sampled within the compost and in the base plenum had minimum oxygen contents of 15% maintained during and after the periods when airflow was being detected. This data indicates that natural convection was the mechanism for aeration during the passively aerated composting process.

Carbon dioxide measurements were made, but on a less frequent basis as the oxygen probe was more accurate and measurements were easier to obtain. All carbon dioxide measurements are in Appendix A.

The volume was reduced during the process by 0.06 m^3 , slightly higher than the reduction observed over the initial phase of trial 3 (Figure 5.9). The volume reduction occurred over a period of 48 days from the time the material was turned. The most significant reduction occurred after the material was added to the chamber, and like the initial phase of trial 3, the reduction was due to settling.

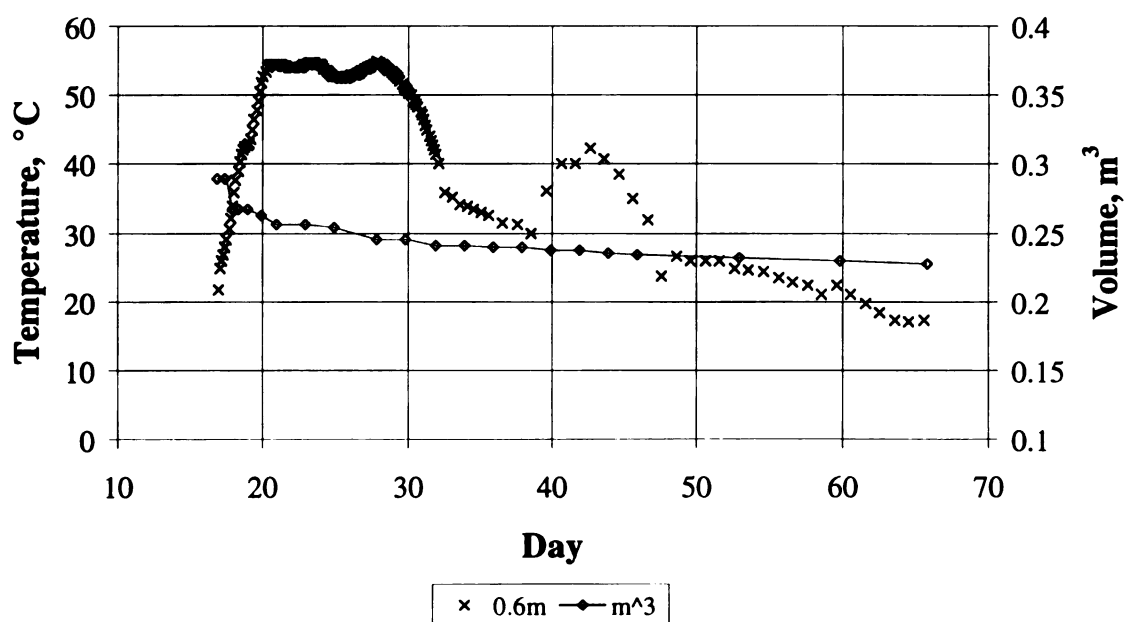


Figure 5.9: Volume of Compost – Trial 3, After 1 Turn.

The most pronounced volume reduction through the rest of the process occurred when temperatures were near the observed maximums indicating the reduction was due from microbial activity.

5.2.4 Composting Trial Run 4 – Initial Stage

A fresh mixture of 1:1 dairy manure to pine wood chips was used to see if the results in trial 3 could be repeated. A thorough mass and moisture balance was conducted. The ambient temperature and oxygen content measured in trial 4 are presented in Figure 5.10.

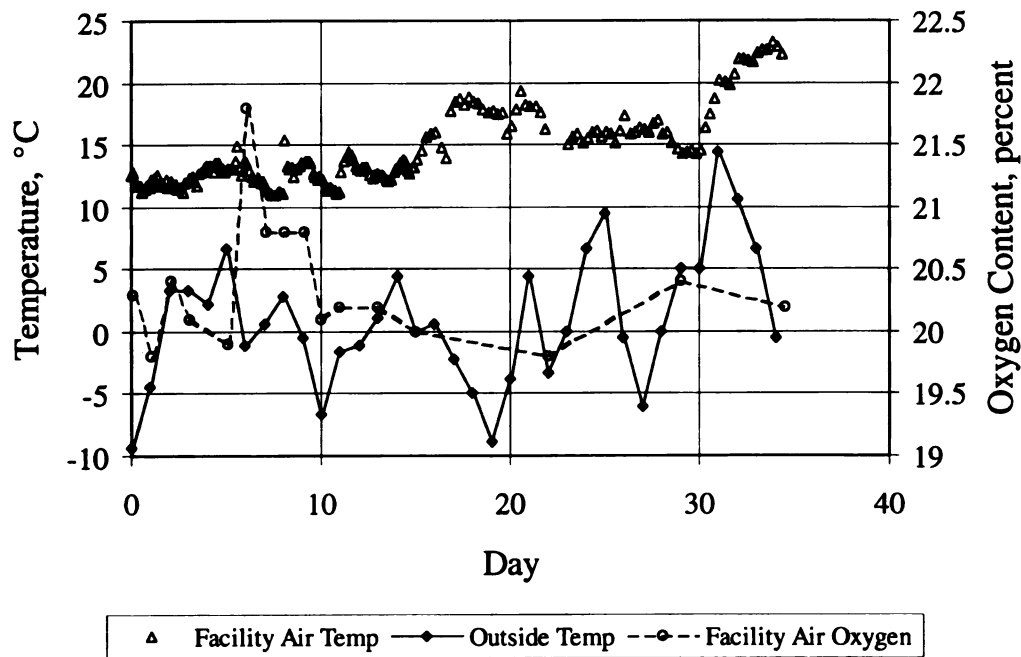


Figure 5.10: Ambient Temperature and Oxygen Content Measurements – Trial 4, Initial Phase.

Pigs were present for the duration of the trial and may account for oxygen contents that were consistently lower than the atmospheric standard of 20.95%. The exception was a spike observed on day 6 and coincides with when the doors to the outside were open for an extended period of time for cleaning purposes.

The moisture content, bulk density, and mass of dry compost, as well as mass of water in the compost, are summarized in Table 5.5. A bulk density of 324 kg/m³ at the 61-97 cm layer was the highest measured and the overall bulk density increased throughout the composting process which is consistent with Rynk (1992), Haug (1993), Michel et al. (1995), and Epstein (1997). Initial moisture content was near the desired starting level as opposed to trial 3 where the levels at the start were too dry.

Table 5.5. Moisture Content, Bulk Density, Compost Mass, and Water Mass of Initial Compost, Compost After 1 Turn, and Final Compost Mixture– Trial 4.

Date	Height, cm	Moisture Content, percent	Bulk Density, kg/m ³	Dry Compost Mass, kg	Mass of Water, kg
2/25/97	0-46	63.1	181.3	13.4	25.8
	46-61	62.7	176.1	18.3	30.7
	61-97	62.7	207.4	18.4	31.2
	97-122	65.8	176.9	15.7	26.9
	Total	63.9	185.2	65.9	114.6
4/1/97	0-46		236.9	12.3	14.4
	46-61		271.7	12.1	14.2
	61-76		324.3	14.4	16.9
	76-94		174.7	23.3	27.3
	Total	54.0	226.5	62.1	72.8
5/17/97	0-46	49.6	265.5	23.6	49.6
	46-76	53.1	285.6	38.1	53.1
	Total	51.3	277.5	61.7	51.3
6/14/98		46.7		61.4	

The dry compost mass was used in evaluating the decomposition rate (k) used in the Keener et al. (1993) kinetics model. The water mass was used in predicting velocities required to account for the moisture loss. These values and models will be discussed later (see Section 5.4).

Compost temperature and oxygen, and air velocity are compared in Figure 5.11. The compost process temperatures increased much slower than during trial 3. It took 16 days to reach the optimal temperature range of 55-60°C in trial 4 while it took less than 4 days during the initial phase and after the material was turned during trial 3.

The temperature of the air entering the compost chamber was 5-7°C cooler at the beginning of trial 4 than in trial 3. This may have slowed the process some, but the lack of chemical analysis of the raw materials limits the scope of conclusions that can be drawn between differences in composting rates of trials 3 and 4.

The plateau in temperatures observed after the trial 3 material was turned was also observed during trial 4. The plateau occurred the day after the trial 3 material was turned while it took until day 6 for the plateau to occur in trial 4. The duration of the temperature plateaus was longer than in trial 3 and this yielded an excellent opportunity to study the plateau phenomena more closely.

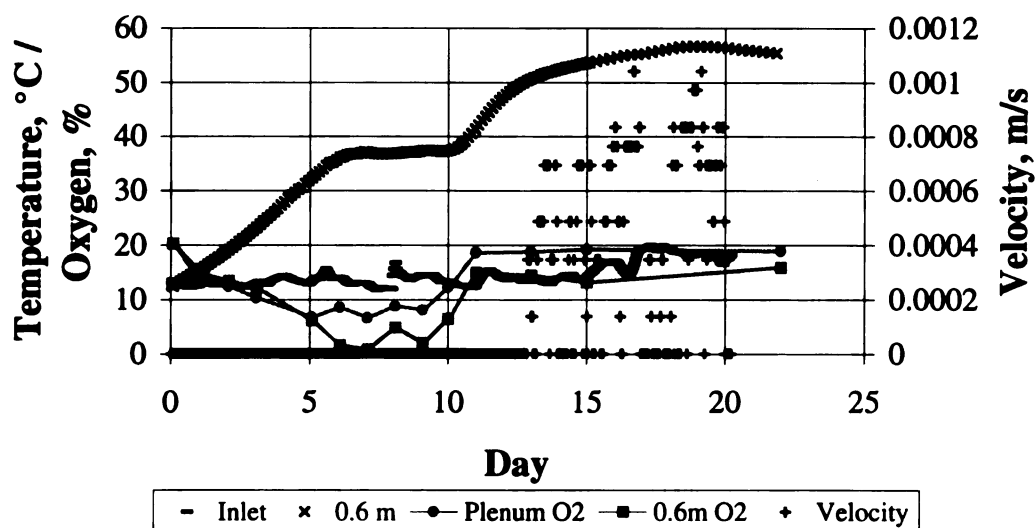


Figure 5.11: Compost Temperature, Oxygen and Air Velocity Measurements – Trial 4, Initial Phase.

Air velocity was measured 3 days after the temperatures began slowing rising from the plateau levels. An oxygen deficit formed and was similar to trial 3 but at a much slower rate. The oxygen deficit in trial 4 lasted for a longer duration than trial 3. Comparison of air velocity and oxygen content in Figure 5.11 shows that air velocity was not detected until a few days after the oxygen content had recovered from the initial deficit. This indicates that undetectable airflow was likely occurring. The prolonged oxygen deficit during trial 4, even after 3 separate gas samples were extracted, also indicated that sampling was having a limited effect on the state of the composting process.

Two smoke gun observations were made during that period where no air velocity was being measured while O₂ content was recovering from a deficit. Smoke was observed being drawn into the inlet, and this verified that airflow was occurring but at undetectable rates.

The first smoke gun observation made on day 7 resulted in an unexpected observation. Smoke was briefly drawn into the inlet but then was pushed out. An additional smoke sample resulted in the same behavior one half hour later. These smoke observations were made when the lowest oxygen content was measured (0.9 percent). This phenomena has not been previously reported and may be associated with the critical aeration breakthrough theorized from the trial 3 data after the material was turned. Further studies should be conducted to try and replicate this behavior and also look closer at mixing of the oxygen and carbon dioxide in the inlet pipe.

The process temperatures, oxygen, and air velocities were detected to be at a relatively steady state after peak temperatures were reached on day 15 continuing through day 20. At this point the Solomat datalogger malfunctioned. This is very important in applying some of the forced aeration based models such as the process kinetic based (Keener et al. 1993), or predicting the air velocity required to account for the moisture removed (Haug 1993).

The compost volume reduction (Figure 5.12) was 0.07 m³ over the 22 days data was collected. Like in trial 3, settling accounted for the most significant reduction

immediately after material was added to the chamber. And like in trial 3, further volume reduction was most pronounced when process temperatures were at their maximum (50-55°C).

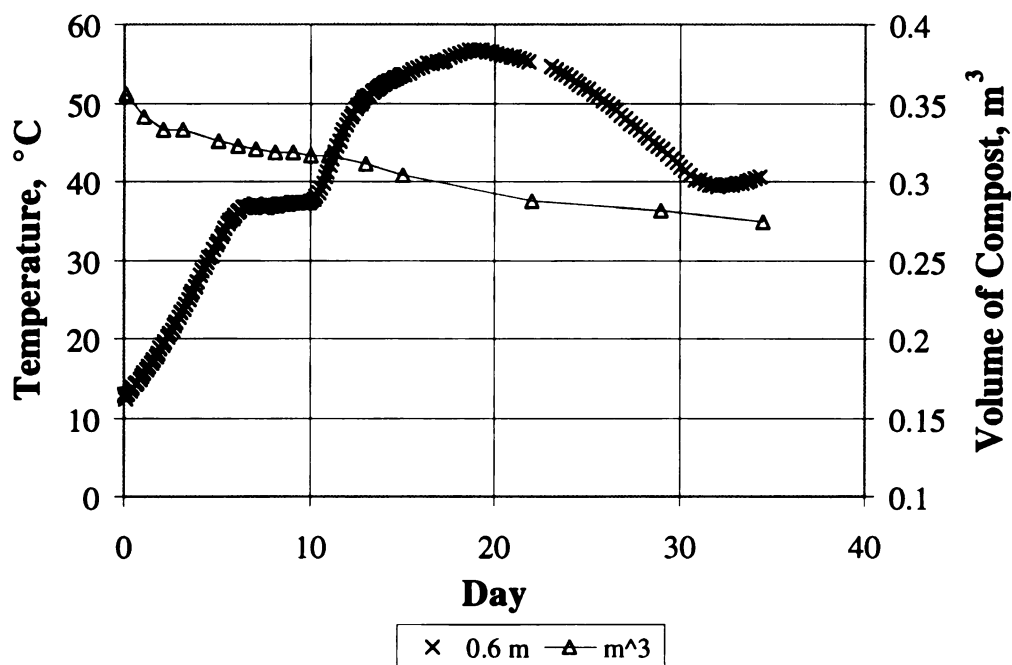


Figure 5.12: Volume of Compost – Trial 4, Initial Stage.

Organic matter (volatile solids) measurements made on triplicate samples of the initial and final compost mixtures were 68% and 49%, respectively. The results of the individual samples are presented in Appendix B. The initial compost mixture had an average standard deviation of $\pm 7\%$, while the final mixture had an average standard deviation of $\pm 2\%$. A relatively small sample (approximately 4-5 g) was measured on a scale accurate to ± 0.001 g. Both the initial and final mixtures had a high concentration of wood chips, but the initial mixture had a higher degree of variation in particle size of the

raw manure and was a potential source of the higher standard deviation. The finished compost was relatively fine and uniform with the exception of the wood chips.

5.3 Permeability

Permeabilities were determined on the compost materials used in both trials 3 and 4. The permeability, K , was measured on hand packed compost for trial 3, after the material was turned, while an *in-situ* core was obtained from trial 4. The raw data used to determine K are presented in Appendix C. The permeabilities obtained from trials 3 and 4 were used to analyze the affect bulk density has on air flow predictions using the Darcian based flow model.

5.3.1 Composting Trial Run 3 – Following 1 Turn

The permeability of the compost material used in trial 3 was determined on 4 different dry weight bulk densities. The material was hand packed to the desired bulk density, and the moisture content was 55%. Air was forced through the chamber from the bottom and the pressure drop across the inlet and exhaust was measured. The airflow rates were varied, and the resulting changes in pressure drop over the length of the core were plotted in Figure 5.13. Bulk density had a dramatic on the slope of the curves. The slope of the curves were used in determining K at each bulk density.

The resulting permeabilities and their respective bulk densities for the hand packed compost analyzed in trial 3 are reported in Table 5.6.

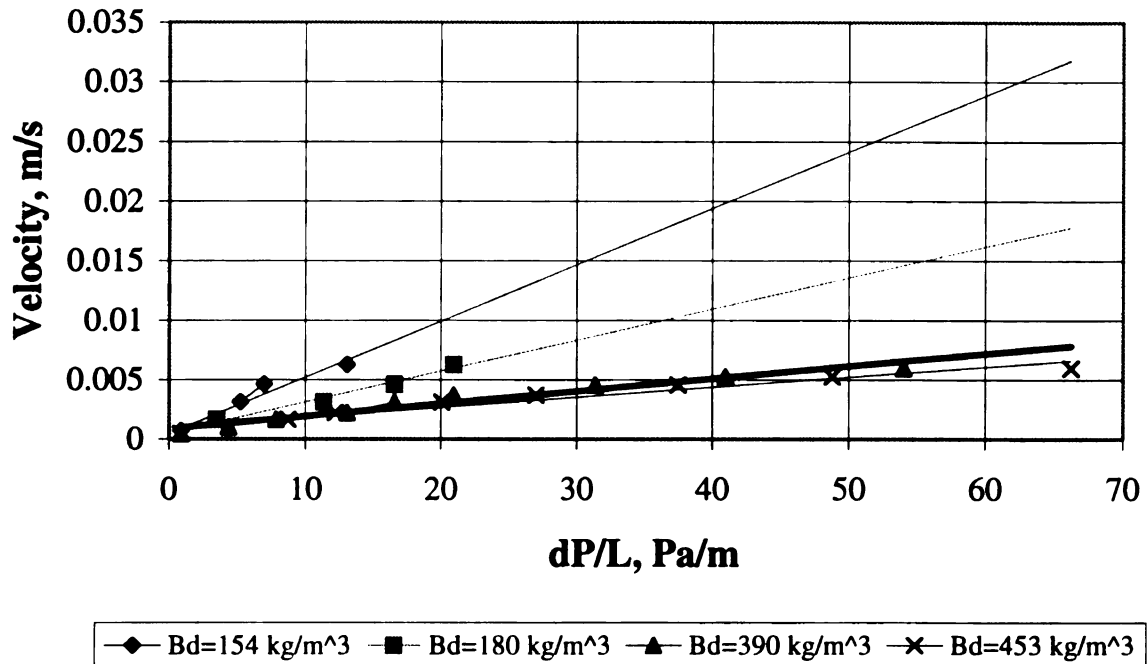


Figure 5.13: Velocity And Pressure Drop Relationship Used For Determining Permeability - Trial 3 After 1 Turn

Values of K reported by Lynch et al. (1996) are within reasonable range of the various K measurements made on the compost with different bulk densities. Since no mixture similar to the mixture used in trials 3 and 4 was reported, and no bulk densities, the bulk density of the compost in the chamber and the *in-situ* core were measured.

Table 5.6. Permeability at Different Bulk Densities of Hand Packed Cores- Trial 3 After 1 Turn

Bulk Density (kg/m ³)	159	180	390	452
Permeability (m ²)	9.66x10 ⁻⁹	5.34x10 ⁻⁹	2.17x10 ⁻⁹	1.73x10 ⁻⁹

5.3.2 Composting Trial Run 4 – Initial Stage

The permeability of the compost material used in trial 4 was determined from one *in-situ* core placed on the base of the chamber before material was added. The measurements were carried out on the core in the same manner as described in section 5.3.1 and the data used to determine K is plotted in Figure 14.

The resulting permeability of the *in-situ* core was determined from the slope of the linear relationship in Figure 5.14, and was found to be $K=3.23 \times 10^{-9} \text{ m}^2$. The bulk density of the core was determined to be 217 kg/m^3 and had a moisture content of 54%.

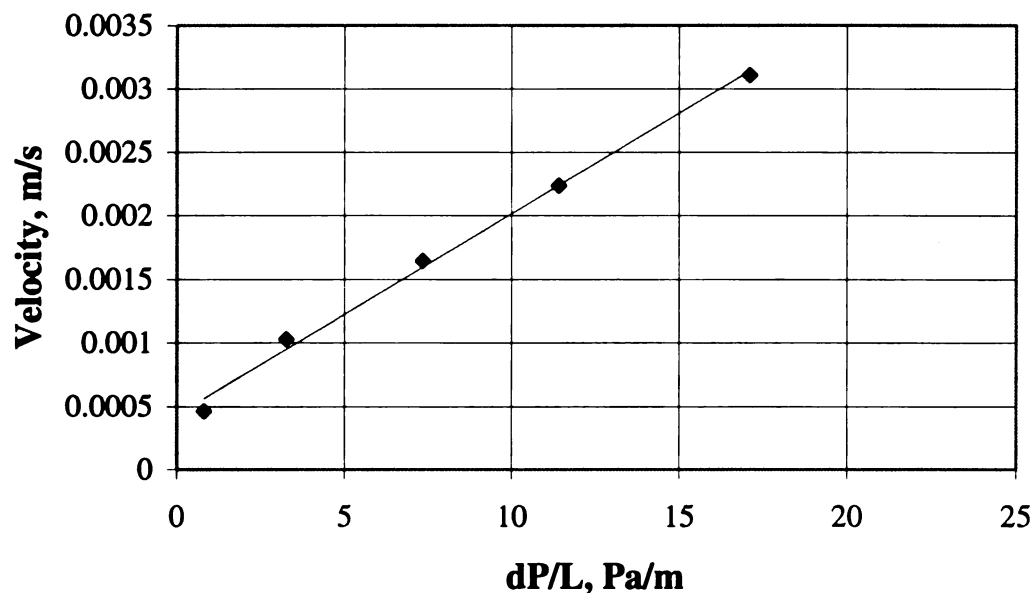


Figure 5.14: Velocity And Pressure Drop Relationship Used For Determining Permeability - Trial 4, Initial Stage

5.4 Decomposition Rate – Trial 4

The mass balance conducted during trial 4 allowed for the determination of the decomposition rate (k) for the composted material. The value of k was important for modeling air flow based on the Keener et al. (1993) process kinetics based model. Table 5.7 summarizes the dry mass of the compost and mass of water at different times throughout the compost. The day 474 reading was made in order to provide the equilibrium mass (m_e) required in determining k by equation 4.4.

Table 5.7. Compost and Moisture Mass Balance, and Mass Ratio For Trial 4 Compost Material

Day θ	Dry Mass, kg $m(\theta)$	Moisture Mass, kg	Mass Ratio, kg/kg mR
0	65.9	114.6	1
34.2	62.1	72.8	0.16
80.2	61.7	51.3	0.07
474	61.4	28.6	0

The mR relates the amount of decomposable material available relative to the m_e of the compost. A majority of the decomposable dry mass was reduced by day 34.2. The compost was in a finished state as defined by Rynk (1992) by day 80.2.

The decomposition rate (k) was determined by evaluating the exponential relationship between time and mass ratio according to equation 4.4. The relationship is shown in Figure 5.15 and the k was found to be -0.0361 kg/kg-day.

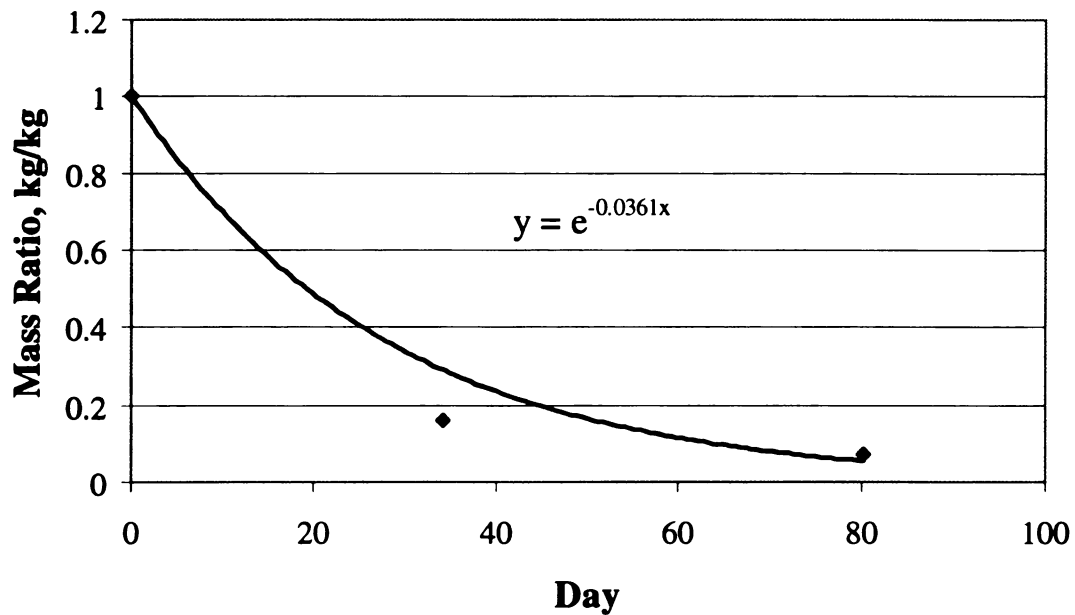


Figure 5.15: Decomposition Rate Curve – Trial 4, Initial Stage

5.5 Predicted Velocities

Three different modeling approaches were used to analyze and compare the measured and observed data. The Darcian flow based model used by Lynch et al. (1995) was the only model developed based on a passively aerated composting system. The two other models, predicting air flow to maintain process temperature (process kinetics based), and predicting air flow to account for moisture removal, were originally

developed for analysis of forced-aeration composting systems where composting is maintained as a steady state process.

5.5.1 Darcian Flow Model

5.5.1.1 Composting Trial Run 3 – Following 1 Turn

Air velocities were predicted based on Darcy's Law using the different permeabilities (K) measured on the trial 3 cores packed at different bulk densities. The inlet and compost air was assumed to be dry and oxygen and carbon dioxide levels constant (first assumption listed in Section 4.9.1). The predicted air velocities using the different K values are compared with measured air velocities in Figure 5.16.

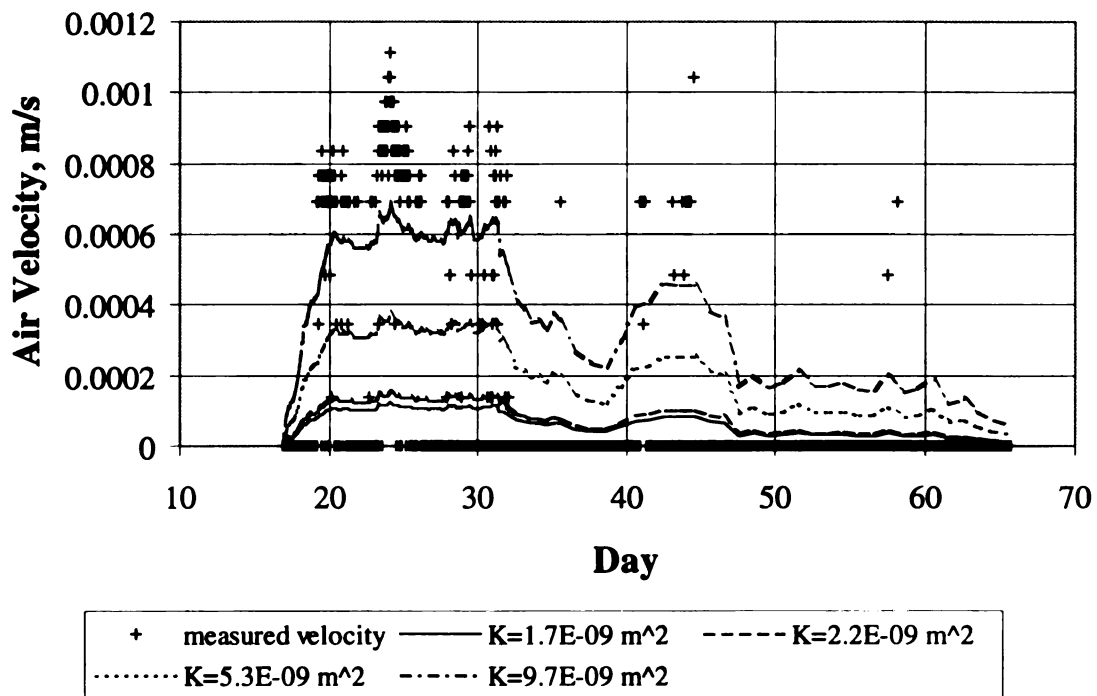


Figure 5.16: Temperature and Predicted Air Velocities of Different Permeabilities – Trial 3, After 1 Turn

The highest K produced the highest predicted velocities, but the highest K ($9.66 \times 10^{-9} \text{ m}^2$) is higher than the value for relatively porous wood chips reported by Lynch et al. (1995).

Predicted air velocity trends shown in Figure 5.17 were developed for each assumption listed in Section 4.9.1 in order to make comparisons to measured air velocities. The trial 3 packed core with a K of $5.34 \times 10^{-9} \text{ m}^2$ was used because it was relatively close to the trial 4 *in-situ* core K and yielded velocity trends higher in magnitude and more pronounced than trends developed with lower K's (Figure 5.16).

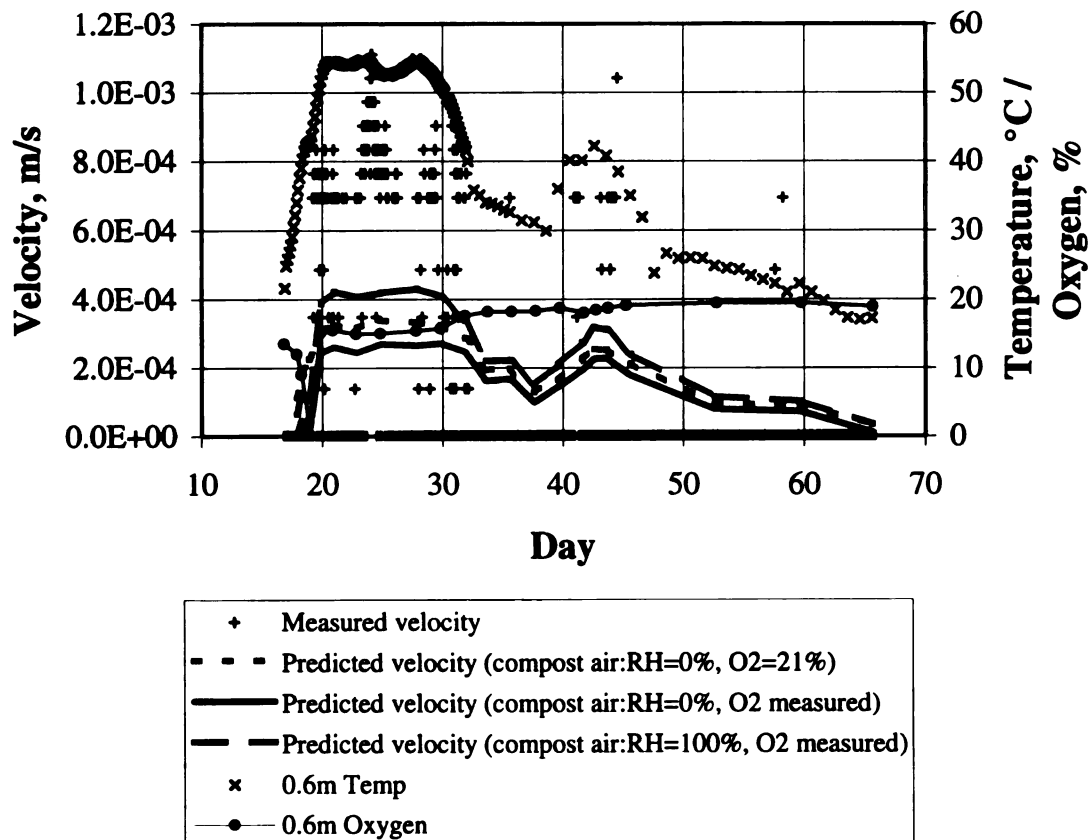


Figure 5.17: Darcian Predicted Air Velocities – Trial 3, After 1 Turn

5.5.1.2 Composting Trial Run 4 – Initial Phase

Predicted air velocity trends were predicted based on the Darcian model and the assumptions listed in Section 4.9.1. The predicted trends are compared against each other and with measured velocity in Figure 5.18. The K obtained from the *in-situ* core was used in all predictions. The temperature and oxygen content of the compost air measured at 0.6-m and used in predicting air velocity are also shown. The oxygen deficit in Figure 5.18 was where the largest difference occurred between the velocities predicted with measured temperature and oxygen content, and the velocities predicted with just the temperature.

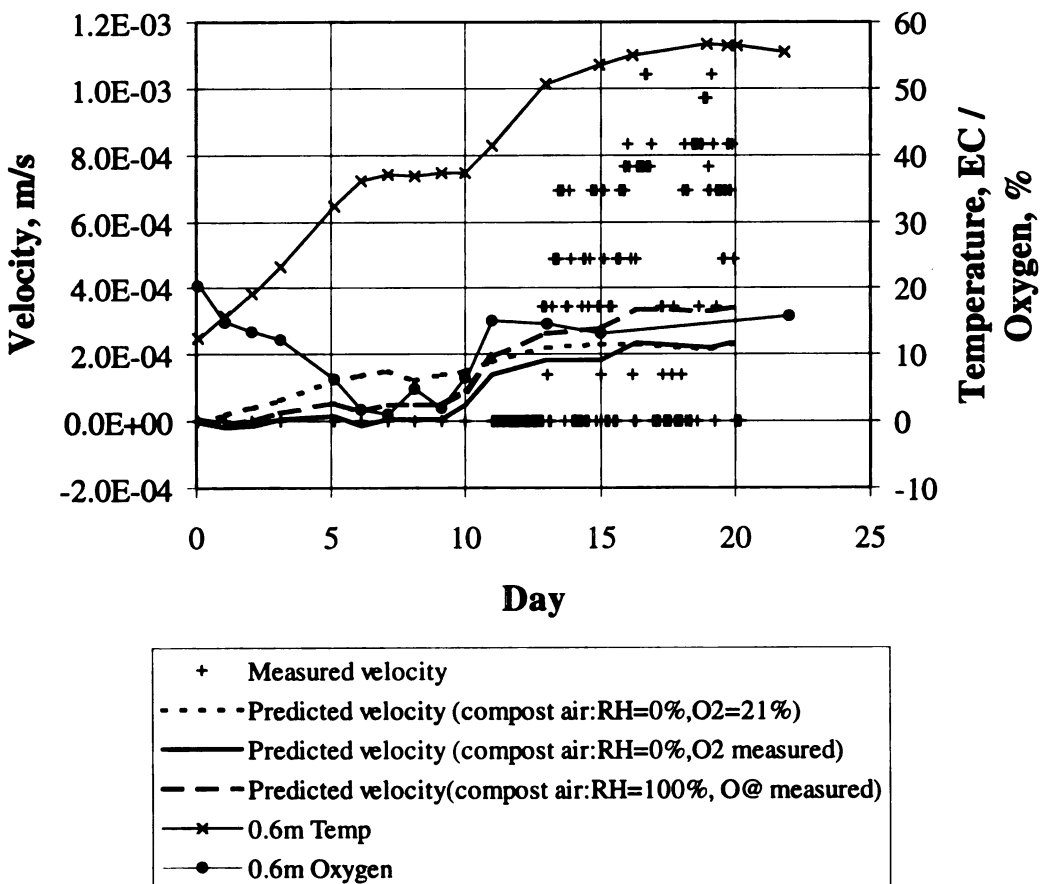


Figure 5.18: Darcian Predicted Air Velocities – Trial 4, Initial Phase

5.5.2 Process Temperature (Kinetics) Based Flow Model

Predicting air velocities based on maintaining a constant compost temperature (equation 4.5) was conducted using only trial 4 data. Because of the difference in overall process speed between trials 3 and 4 based on compost temperature data, the decomposition rate (k) determined for trial 4 would likely be substantially lower than trial 3. Therefore, application of k in predicting air velocities using equation 4.5 was limited to trial 4 only.

The kinetics based model developed by Keener et al. (1993) assumes that composting occurs under steady state conditions observed with forced aeration systems but not with naturally aerated systems. But temperature and gas concentration data from trial 4 observed a period of relatively little change. Using temperatures recorded during that period, air velocities were predicted and compared to velocities measured at the same time the temperature was measured.

The predicted and measured velocities for selected temperatures from trial 4 are summarized in Table 5.8. The model assumes that the air exiting the compost is saturated and that the temperature at the surface was the temperature throughout the compost. Because the data from this study shows that the temperature varies throughout the compost, air velocities was predicted to maintain temperatures measured at both the surface and where maximum temperatures most often occurred, at 0.6-m height. The predicted velocities when temperature was taken from the 0.6 m height were very close to

measured velocities, and much closer than when temperature were taken from the surface.

Table 5.8. Process Temperature Based Predicted Velocities and Measured Velocities – Trial 4, Initial Phase

Day	Inlet Temp °C	Surface Temp °C	0.6-m Temp °C	Measured Velocity, m/s	Predicted Velocity (temp taken at surface) , m/s	Predicted Velocity (temp taken at 0.6 m) , m/s
12.95	13.5	41.3	50.6	3.47E-04	9.06E-04	5.37E-04
15.08	14.7	42.1	53.7	6.94E-04	10.10E-04	5.04E-04
16.30	15.3	40.8	55.0	4.86E-04	10.60E-04	4.73E-04
19.08	18.5	39.6	56.6	6.94E-04	11.70E-04	4.31E-04
19.83	16.8	38.8	56.5	6.94E-04	12.20E-04	4.33E-04

5.5.3 Moisture Removal Based Flow Model

Air velocities based on moisture removal were predicted based on the trial 4 moisture and mass balance data. The model is based on the temperature data and the water carrying capacity of air related to those temperatures. Air velocity is estimated based on how much moisture is removed during the compost process. As with the process temperature based model, the system must be at steady state for the model to apply (Haug 1993).

The predicted velocities to remove the moisture lost during trial 4 are summarized in Table 5.9. The predicted velocities were compared to the same measured velocities used in the comparison of process temperature based predictions in Table 5.8. The predicted velocities to account for the moisture lost during the trial 4 composting process were the lowest of all the models analyzed.

Table 5.9. Moisture Removal Based Predicted Velocities and Measured Velocities – Trial 4, Initial Phase

Day	Inlet Temp °C	Surface Temp °C	0.6-m Temp °C	Measured Velocity, m/s	Predicted Velocity (temp taken at surface) , m/s	Predicted Velocity (temp taken at 0.6 m) , m/s
12.95	13.5	41.3	50.6	3.47E-04	2.26E-04	1.35E-04
15.08	14.7	42.1	53.7	6.94E-04	2.16E-04	1.14E-04
16.30	15.3	40.8	55.0	4.86E-04	2.25E-04	1.09E-04
19.08	18.5	39.6	56.6	6.94E-04	2.49E-04	0.97E-04
20	16.8	38.8	56.5	6.94E-04	2.61E-04	0.97E-04

5.6 Stoichiometric Demand

The oxygen and carbon dioxide content data was checked against the simplified stoichiometric respiration model given in equation 4.15. At the time the lowest oxygen was measured (0.9% on day 7), an estimation of oxygen consumed and carbon dioxide liberated was made based on the reduction of carbon estimated from the organic matter content measured in trial 4.

The initial organic matter measured in trial 4 of 68% decreased to 49% during the composting process. Based on the decomposition rate (k) estimated from the dry mass data, an estimate of dry compost was made at the time when the lowest oxygen content of 0.9% was measured at 0.6-m height. The average oxygen content of air sampled from the compost material and chamber plenum was 6.2%. The plenum measurement was included because it was the only representation of what the oxygen content was at the base of the compost.

The estimated mass was used to estimate the amount of organic matter present. From the organic matter, the amount of carbon was estimated based on the assumption that there is 0.54 kg of carbon in 1 kg of OM. When the masses were converted to molar equivalence and the O_2 and the CO_2 total were based on the standard atmospheric content of 20.98%, an estimated 8.8% of oxygen was required to reduce consume the carbon, and an estimated 12.2% of CO_2 were liberated, assuming that no airflow was occurring.

The stoichiometric demand model was simplified because the chemical makeup of the compost was not known. The estimated oxygen compares (8.8%) well with the average of the measured oxygen (6.2%), but in order to more accurately model oxygen demand based on a stoichiometric balance equation, the exact composition of the compost must be first determined.

CHAPTER 6

DISCUSSION OF RESULTS

6.1 Experimental Results

6.1.1 Composting Trial Run 1

The temperatures in trial 1 exceeded 70°C (Figure 5.1) and foul odors were noticeable by day 2 indicating the system had gone anaerobic. This was likely a result of the 4:1 dairy manure to leaf mixture made against the recommendations of Rynk (1992) for dairy manure. But the objective of using this mixture was to test the capability of the chamber to initiate and maintain a composting process.

Insulating the chamber was very important in maintaining relatively even temperature distribution laterally through the compost (Figure 5.2). One hot water blanket was wrapped around the chamber during trial 1, and an additional hot water blanket was wrapped around the chamber for trials 3 and 4.

6.1.2 Composting Trial Run 3: Initial Stage

The highest compost temperatures were measured at the 0.6 m and 0.9 m height (Figure 5.4) and exceeded 50°C 2 days after the materials were initially mixed. Optimum composting process temperatures for naturally and passively aerated composting systems are 50-60°C (Epstein 1997). Within 1 day of exceeding 50°C, the temperatures at 0.6 m and 0.9 m decreased rapidly indicating the process was slowing. This decrease in compost temperatures lagged by a 1 day a similar decrease in air temperature measured at the chamber inlet. The decrease in compost temperature may

have resulted from a lack of sufficient moisture removed by natural convection rather than the decrease in inlet air temperature.

An oxygen deficit had formed in the compost mixture by day 2 of the process (Figure 5.4). But by day 3, the oxygen levels in the compost had recovered to levels higher than measured when the compost materials were initially mixed and added to the chamber. Air velocity was detected and measured twice within 5 hours of the peak temperature measured at the 0.9-m height (58°C). The air velocity measurements also occurred within 1 day of the recovery of oxygen measured in the compost. The oxygen recovery observed 1 day prior to air velocity measurements indicates airflow, although undetectable, was likely occurring from convection.

Airflow during composting removes heat and moisture from the composting process, and if either becomes a limiting factor the process will slow (Epstein 1997; Haug 1993). Visual inspection of the material indicated the compost had dried substantially since being added to the chamber. The increase in temperature of the compost increased the water carrying capacity of the air, and airflow would have likely removed a significant portion of that moisture.

Water was added on day 4 resulting in an immediate increase in compost temperatures. Compost temperatures at the 0.6-m and 0.9-m height exceeded 50°C for just over 3 days and then gradually decreased. The compost temperatures at 0.9-m height

were initially the highest measured in the compost, but after 6 days they were lower than the temperatures measured at the 0.3-m and 0.6-m heights.

The wet weight moisture content of the compost material when sampled initially and when removed for turning was 42% and 37%, respectively (Table 5.2). Moisture contents (wet weight) needed to maintain optimal temperatures during composting range from 55 to 69% (Epstein 1997). Therefore, it was concluded that moisture was the limiting factor resulting in optimal temperatures being maintained only briefly during the process.

From Figure 5.6, compost volume did not change between day 4 to 6, but after day 6 the volume decreased which is when the compost temperature at the 0.9-m height peaked and began decreasing. This suggests that the location of highest compost temperatures and consequently highest biological activity changes as the overall volume of compost decreased during the process.

6.1.3 Composting Trial Run 3: Following 1 Turn

As discussed in Section 6.1.2, the temperature decrease during the initial phase of trial 3 was not due to a deficiency in oxygen but more likely from a lack of adequate moisture. Although water was added, the process had observed only a brief increase in compost temperatures. The material was removed incrementally in order to get a moisture content profile. The materials were mixed and water was added before being

put back in the chamber. This procedure constituted what is referred to as turning the compost.

Recommended turning frequency of naturally aerated windrows and piles varies greatly from practice to practice and from mixture to mixture (Michel et al. 1995). Rynk (1992) recommended turning if temperatures decreased steadily over a period of days and implied the temperature decrease is due to oxygen deficiency in the compost. Turning would release carbon dioxide that built up from microbial respiration, but oxygen introduced by turning is typically depleted in the matter of hours (Epstein 1997; Lynch et al. 1995; Michel et al. 1995; Lufkin et al. 1995; Haug 1993; Miller et al. 1989). The compost material was “turned” during trial 3 to determine the moisture content and not because of a lack of oxygen.

The water added to the trial 3 compost material brought the moisture content up to 67% (Table 5.3), and was within the optimal range of 55 to 69% needed to achieve optimal temperatures (Epstein 1997). As a result, maximum compost temperatures occurred at the 0.6-m for the entire process. The 0.9-m thermocouples were exposed due to the reduced volume and height of the compost mixture that occurred from both settling and decomposition of materials and were thus not representative of the compost air.

Compost temperatures at the 0.6-m height of the turned material were maintained above 50°C for 10 days (Figure 5.8), almost 8 days longer than when the compost raw materials were initially mixed. The reason optimal process temperatures were maintained

for a longer duration after the material was turned was likely due to the higher moisture content of the turned material.

As with the initial phase of trial, an oxygen deficit formed immediately after the “turned” compost material was added to the chamber. However, the oxygen contents in the compost fell below the critical 5% aerobic/anaerobic level which did not occur with the deficit that formed during the initial phase of trial 3.

The recovery of oxygen was similar to the trial 3 initial phase recovery, and both trends were similar to those reported by Sartaj et al. (1997) for passively aerated systems. In fact, the oxygen recovery for both the initial phase and after the material was turned occurred much quicker than the data reported by Sartaj et al. (1997) for forced aerated systems. A temperature plateau occurred at about the same time the lowest oxygen contents were measured (Figure 5.8). The plateau likely resulted from the low oxygen levels (below 5%) which would have slowed microbial respiration thus reducing the amount of heat added to the system. As with the initial phase, the oxygen recovery of the turned compost was thought to result from airflow.

The first known measured air velocity through a passively aerated composting media was made during the initial phase of trial 3, but on only two occasions. A sustained measurement of airflow was made during trial 3 after the material was turned (Figure 5.8). Airflow was detected just after compost oxygen contents began recovering

and temperature of the compost increased from the observed plateau. It is not certain why airflow initiated when it did, but two possible reasons are explored.

Smoke gun observations made indicated that some mixing of air was occurring in the inlet pipe just prior to measurable airflow. On two occasions the smoke was observed to flow out of the inlet and may have been related to a release of accumulated carbon dioxide gas as indicated by low oxygen contents measured in the plenum (Figure 5.8). Carbon dioxide is denser than oxygen and any significant accumulation would likely vent out of the bottom if a pathway were available. The inlet pipe would then serve as that pathway.

Carbon dioxide venting out the inlet pipe would likely impede airflow. Venting would likely reduce the carbon dioxide content in the compost to a point that it did not impede airflow and allowed for increased microbial activity. The increased microbial activity could have increased compost temperatures enough to initiate airflow.

Another reason possibly contributing to the breakthrough of airflow is moisture reduction. The role of moisture in terms of when airflow broke through was thought to be significant. But without actual measured values during the periods when air flow was first detected, the affect cannot be accurately assessed but only implied. Das and Keener (1995) reported that moisture contents above 60% had a clear influence on compactability and air permeability of the compost media. As moisture contents dropped

below 60%, dramatic decreases in pressure drop across a column of compost were reported which means there was less resistance to flow

The turned material added to the chamber had a moisture content of 67% (Table 5.4). The carrying capacity of the compost air increased with the temperature. Assuming that some airflow was occurring below the detection level of the instrumentation, the warmed air would have risen out of the chamber and removed some moisture from the system. This could have led to a decrease to a critical level, perhaps the 60% cited by Das and Keener (1995), resulting in the breakthrough of airflow, oxygen, and increase in temperature.

Air velocity measurements did vary greatly during trial 3 after the material was turned. Fluctuations in ambient air temperature and relative humidity (Figure 5.7) and also to the air in the compost media itself would likely have an affect on the low order magnitudes of velocity associated with passively composting systems.

6.1.4 Composting Trial Run 4

Maximum compost temperatures at the 0.6-m height were maintained above 50°C for 9 days during the initial phase of trial 4 (Figure 5.11). Compost temperatures at 0.6-m were above 55°C when data collection was ceased due to instrumentation problems. The thermocouples at the 0.9-m height were exposed and are not presented. The initial moisture content of the mixture was 64% (Table 5.4) and was within optimal ranges cited by Epstein (1997) and Rynk (1992).

The process temperatures rose slower during trial 4 than during both phases of trial 3. This was thought to be due to the state of the dairy manure when collected before the trials. Dairy manure used in all trials of this study was taken from the MSU Dairy Farm after having been stockpiled outside for approximately one week. The trial 3 manure was obtained in the late summer while the trial 4 manure was obtained in the winter and under frozen conditions. The onset of decomposition would take longer with the manure stockpiled under frozen conditions thus resulting in the slower increase in process temperatures observed during trial 4.

The temperature plateau observed after the material was turned in trial 3 was also observed during the initial phase of trial 4. The plateau in compost temperatures observed during trial 4 occurred over a longer period of time (Figure 5.11) than in trial 3. The reasons for this trend are best described by analyzing at the oxygen content, temperature, and air velocity data simultaneously.

Figure 5.11 shows that air flow did not begin until 2 days after compost temperatures began increasing from the plateau. During that plateau oxygen contents fluctuated below the critical 5% level. Compost temperatures did not increase from the plateau until 2 days after oxygen contents began recovering. Smoke gun observations made during the oxygen deficit of trial 4 indicated some airflow was occurring into the compost chamber at levels undetectable to the velocity probe. This verifies the

assumption made in Section 6.1.3 that airflow was occurring even though it was below the detection limits of the instrumentation.

During trial 4, two smoke gun observations showed smoke being drawn in and then pushed out on a repeated basis. Smoke was observed to flow out of the inlet pipe in trial 3, but not on the repeated basis observed during trial 4. These observations were made towards the end of the oxygen deficit (day 8 and 9) and just before compost temperatures increased from the plateau. The fluctuations in smoke were thought to be related to the build up and venting of carbon dioxide. The smoke gun observations did show there was a great deal of fluctuations in the inlet air and could account for the high degree of variations in measured air velocity.

Without continuous moisture content measurements an accurate assessment of what factor(s) accounts most for the airflow breakthrough is not possible. However, the fluctuation of oxygen in the compost observed during the oxygen deficit did not result in fluctuations in temperature measured at the same times and heights as the oxygen indicating that even if airflow was occurring, it was not enough to supply microbes and significantly effect the biological activity. Venting of carbon dioxide inferred from the oxygen measurements would not seem to be the main reason continuous airflow was initiated. Therefore, changes in moisture content (reduction) as discussed in Section 6.1.3 were thought to be the main factor as to when continuous airflow broke through in trial 4.

The rate of compost volume reduction for trial 4 (Figure 5.12) as measured by changes in height of the compost surface was highest within the first 3 days after the material was added. The same was observed for both phases of trial 3 (Figures 5.6 and 5.9). A majority of volume reduction in all cases was likely due to settling. Decomposition accounted for a much smaller decrease in compost volume for the remainder of the composting process.

A mass balance was conducted for trial 4 (Table 5.6) and was very important in modeling the composting process using process kinetic derived and moisture balance derived expressions. Error associated with mass balance was minimized by the low sensitivity of the scale used (± 0.1 kg). Compost mass was weighed as individual layers were added or removed when material was turned. The mass weighed included compost material and moisture present. Dry compost mass was estimated by subtracting the fraction of water estimated by multiplying the measured moisture content by the total mass. One way to improve mass balance would be to set up the chamber on a scale and conduct the composting process.

Dry weight bulk density was estimated for the overall compost mixture and at the individual layers from which compost mass was weighed. Dry compost mass and mass of water were both reduced most during the initial phase of composting. The reduction was much less after the material was turned. Bulk density increased throughout the composting process from 185 kg/m^3 to 278 kg/m^3 .

The 61-76 cm layer had the highest bulk density when the material was removed for turning. This is also the layer where highest temperatures were recorded during the composting process. The highest temperatures would be associated with the highest level of microbial activity and would have decomposed more material than at any other location. Moisture would have likely condensed just above where highest temperatures occurred. Therefore, there could have been higher moisture contents at that layer than at any other location throughout the compost.

Organic matter (volatile solids) measurements were made on samples taken of the initial and final compost of trial 4. Organic matter measurements had several potential sources of error, the first being the relatively small amount of sample used in analysis (approximately 5 grams). The presence of wood chips or pebbles could vary the weight greatly. Great care was made in ensuring samples measured had the same relative amount of wood chips present. Organic matter contents of the initial mixture and final compost and reduction over the trial 4 period were within reason of values reported for various materials by Epstein (1997), Michel et al. (1995), and Haug (1993).

Organic matter determinations do provide a rough estimate of biological activity, but their overall application is limited because as Michel et al. (1995) noted it lacks specificity and sensitivity. Materials readily metabolized, less readily metabolized, and not metabolized during any reasonable composting process do not get separated during organic matter testing.

6.1.5 Compost Permeability

Permeability was a relatively easy parameter to obtain and measured values were comparable to those reported by Lynch et al. (1995). Published data on the permeabilities of various materials and mixtures was found to be limited and no bulk density or moisture content data was reported with the published values. Higher bulk densities reduced the permeability (Table 5.6) which was expected, as permeability is a measurement of pressure drop over a length of porous media at different velocities (Equation 3.1).

The in-situ core obtained from trial 4 had a measured permeability and bulk density that was within the same range when compared to the various permeabilities measured on cores hand packed to different bulk densities in trial 3. The moisture content which was hypothesized to be one of the main factors of when measurable air flow would occur was relatively the same for the hand packed cores measured during trial 3 and the *in-situ* core from trial 4. Changes in the permeability factor therefore could only be attributed to changes in bulk density. Studying the affect moisture content has on permeability could possibly allow a means to better evaluate how moisture content affects overall airflow through a composting media.

Hand packed cores would be sufficient for evaluating permeability as long as they are packed to a bulk density representative of actual composting conditions. The method is a quick and easy means of obtaining data needed for evaluating and predicting airflow through a composting media based on Darcian flow. Future research efforts should

include the development of an expression that accounts for bulk density and moisture content when determining permeability in order to improve the accuracy of predicting airflow through a composting media using the Darcian model.

6.1.6 Compost Decomposition Rate

Decomposition rate (k) was evaluated using the approach presented by Keener et al. (1993) for deriving an expression from experimental data. The resulting k was within the range reported for sludges and cage layer manure mixed with corn cobs (Keener et al. 1993). The expression for k also allowed for estimating the mass of material at any time of the composting process.

The compost mixture used in trial 4 was the same as in trial 3 but the decomposition rate (k) determined from trial 4 could not be applied for trial 3. There were significantly different trends in temperature and oxygen content over time observed, especially at the initial phase of composting that would have likely resulted in a much different k for trial 3.

The trial 4 compost temperatures took longer to rise than the temperatures for both phases of trial 3. Therefore, the decomposition rate should be determined on a case by case basis because even similar materials and mixtures decompose at different rates depending on a variety of factors including how the materials were handled prior to composting as well as changes in ambient conditions during composting.

6.2 Assessment of Model Behavior and Characteristics

All models analyzed assumed that temperature was uniform throughout the composting media. But this has been shown to be otherwise with data. Design temperatures used in modeling are picked within the 50°C to 60°C optimal range (Lynch et al. 1995; Haug 1993; Keener et al. 1993). Further development of more dynamic models has been limited due to the inability to verify passively or naturally aerated composting process models, so assuming uniform temperature was necessary in order to make a general assessment as to whether the magnitudes of the actual air velocities measured made sense or not.

6.2.1 Darcian Flow Based Model

Air velocities were predicted using Darcy's Law for three different assumed conditions of the compost air (Section 4.9.1) and compared to air velocities measured in trial 3, after the material was turned (Figure 5.17), and trial 4 (Figure 5.18). Velocities were also predicted using the trial 3 data (after material was turned) for the different permeabilities measured from the trial 3 material (Figure 5.16).

The predicted air velocities based on Darcy's Law were found to consistently underestimate measured air velocities for both trials. However, the Darcian model allowed for predicting air velocities for periods when no air velocity was measured. There were several smoke gun observations made indicating airflow was occurring although no air velocities were being measured.

Comparing the predicted velocities of the different permeabilities (Figure 5.16), the highest permeability value obtained from the core packed to the lowest bulk density resulted in the highest predicted air velocity values. These highest predicted velocities were still lower than measured indicating that Darcian based flow model underestimated measured air velocities. This discrepancy becomes an issue in the overall efficiency of design and management of larger passively aerated windrows or piles.

The trends of all the predicted velocities in trial 3 after the material was turned matched the trends of the measured air velocities over time. The similarity between predicted and measured air velocity trends is the strongest indication that the measured air velocity was dependent on temperature and was a result of a natural convective driving force.

The velocity trends predicted for the different assumptions made of the compost air in trial 3 (after material turned) were similar. The largest difference between the predicted values was slightly more than 0.0002 m/s (Figure 5.17) on day 2 which is when the lowest oxygen content measurement was made. Both velocities predicted using the oxygen data observed a decrease in air velocity from day 1 to 2 as a result of the oxygen deficit. The velocity predicted with oxygen assumed to be at 21% increased over that same interval.

The most significant result from the trial 3 predicted velocities was that the highest velocities occurred when the compost air was assumed to be saturated, and

compost air density was computed using measured temperature and oxygen content data. Air leaving compost piles can be assumed to be saturated when the compost is at a moisture content greater than 50%, and at 95% when compost moisture contents were in the range of 45 to 50% (Bach et al. 1987). Therefore, assuming the compost air to be saturated was the more accurate way of predicting air velocity. The reason compost air was assumed to be dry is because it simplifies the air density computation based on the Ideal Gas Law (Equation 3.3) as atmospheric pressure (101.3 kPa) can be assumed. The pressure of the air becomes a function of temperature when the air is assumed to be saturated (Weast 1982).

Trial 4 data collection had ceased just as the composting process had reached optimal temperatures. No trends were observed between the predicted velocity and measured velocity for this brief period of time, at least none as obvious as in trial 3. As with the Darcian based predicted velocities from the trial 3 data, trial 4 predicted velocities were lower than a majority of measured air velocities.

An interesting trend was observed from predicting velocity assuming the compost air was dry and air density was computed using temperature and oxygen data (Figure 5.18). Between day 5 and 7, the predicted air velocity trend fluctuated between very low positive and negative values, and this was the same time smoke was observed to flow into and out from the inlet pipe. Assuming compost air was dry when predicting air velocities based on compost air temperature and oxygen data provided an explanation for the phenomena observed with the smoke.

Based on the positive and negative predicted velocity fluctuation observed in trial 4, it may be more accurate to assume the compost air is closer to the humidity of the incoming air when velocities were predicted to be less than 0.0001 m/s (Figure 5.18). Ambient air was assumed to be dry when predicting Darcian based air velocities for both trials 3 and 4. Predicted velocity trends when compost air was assumed to be saturated were higher than the two velocity trends predicted assuming compost air was assumed to be dry for both trials. Therefore, assuming compost air is saturated should be limited to periods where flow moves heated air through cooler regions of the compost resulting in an increase of the humidity of the air.

6.2.2 Flow to Maintain Process Kinetics Model

Air velocities required to maintain specific temperatures based on process kinetics were predicted for a limited number of data points in trial 4 (Table 5.8). The model developed by Keener et al. (1993) was for designing and managing forced aeration vessel systems where maintaining constant temperature is desired. Airflow is required not only for microbial respiration, but also for removing excessive heat evolved from respiration.

Applying this model to a passively aerated system required a period where the process was at or near steady state. For trial 4, the process was assumed to be at or near a steady state process starting at day 13. The model also assumed the air at the exit was saturated and was at the same temperature as the compost.

Velocities were predicted for temperatures measured at both the surface and at 0.6-m height where maximum compost temperature was most frequently measured. The assumption of saturated air could be inaccurate for both locations as the top 2-3 cm of compost were observed to be very dry relative to the rest of the compost, and air would likely be at or near the most vaporized state at the highest temperature. The model application is also limited to a steady state composting process. Therefore, a limited period of trial 4 was assumed to be at steady state based on nearly steady process temperatures measured after day 13.

Predicted velocities were very close to measured velocities when the 0.6-m height maximum temperature was used instead of the surface temperature. The velocity required for maintaining constant compost process temperature decreased as the design temperature increased. Maintaining lower temperatures would require more air to remove larger amounts of heat than at higher temperatures.

6.2.3 Flow to Account For Moisture Removal Model

Predicted velocities based on the moisture removed were done using the same temperature data points measured at the surface and at the 0.6-m height for predicting velocities to maintain design process temperatures (Table 5.9). The overall predicted velocities to remove moisture using both surface and 0.6 m height temperatures were much lower than measured and predicted velocities required for constant process temperature (Table 5.8).

More air flow was predicted when the compost temperature was taken at the surface which makes sense as the surface temperatures which were consistently cooler than the temperatures at 0.6 m height would carry less water and require more airflow to remove equal amounts of water. Epstein (1997) and Haug (1993) both stated that more air was required to remove heat and maintain process temperature than was required to remove moisture as the heated compost air has a very high water carrying capacity compared to the much cooler ambient air.

6.2.4 Stoichiometric Respiration Balance

A final check of the data collected was made through comparing the O_2 and CO_2 contents measured with contents predicted using a simple stoichiometric respiration equation. Predictions were based on assuming that the carbon in organic matter was consumed at a rate that could be predicted using the decomposition rate (k) expression developed from the mass balance data.

The lowest level of O_2 measured during the deficit observed in trial 4 was checked. The carbon consumed since the beginning of the process to the time the lowest O_2 was measured was predicted using the expression developed for k and converted to an equivalent molar mass. Molar mass equivalents were then computed for both O_2 and CO_2 . Based on the atmospheric content of the sum of O_2 and CO_2 gas (20.98%), the O_2 content required by the aerobic microbes to consume the carbon was estimated to be

8.8% and the CO₂ content was estimated to be 12.2%. The average of the different O₂ contents measured in the compost at the time of lowest overall O₂ measured was 6.2%.

In order to more accurately model O₂ and CO₂ based on stoichiometric demand, the exact composition of the compost mixture would need to be determined and a more accurate prediction of carbon consumed would need to be developed. However, based on the wide range of O₂ content observed when the lowest O₂ content was measured (0.9% to 13%), the check did serve to further strengthen confidence in the data collected during the study, mainly trials 3 and 4.

6.3 Comparison of Composting Model Results

All velocities measured and predicted by Darcy's, the process kinetics model, and the moisture removal model are compared in Figure 6.1. Compost air was assumed to be at saturation and inlet air was assumed to be dry for all predicted velocities. The Darcian velocity was based on measured temperature and oxygen contents at the 0.6-m height. Measured velocities were higher than predicted velocities except on day 13 the velocity predicted to maintain the compost at 50°C was the highest.

The relatively low order of magnitude in velocities both measured and predicted raised concerns about the environment in which the study was conducted. Disturbances and possible effects to ambient air properties of the facility from human and animal activity as well as the ventilation system could have effected the air velocity measured at

the inlet of the chamber. These disturbances could account for the consistent variation in measured air velocity.

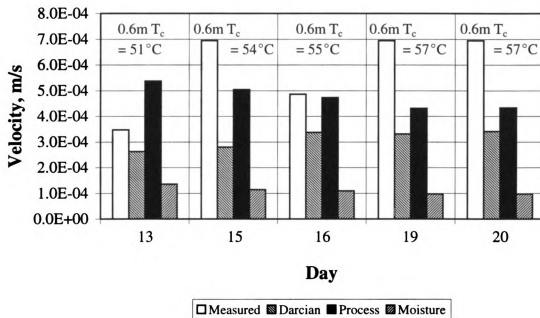


Figure 6.1 Comparison of measured and predicted air velocities – Trial 4.

CHAPTER 7

CONCLUSIONS

1. The experimental apparatus designed and developed for this study was capable of sustaining a passively aerated composting process and allowed for successful measurement of airflow through an inlet pipe placed beneath the base of the composting media.
2. Air velocity measured through the inlet pipe of the experimental apparatus was driven by natural convection. No other driving force could account for the interaction observed between measured air flow, temperature, and O₂ gas content. Air velocities were measured as the temperature differential between ambient air and compost air grew, and was associated with oxygen recoveries from deficits observed shortly after composting began. This breakthrough trend was observed in trials 3 and 4.
3. Measured air velocities was compared to predicted by a Darcian flow based model, a process kinetics based model, and a moisture removal based model. The Darcian model expresses the driving force between compost and ambient air temperatures in terms of air densities and consistently underestimated measured air velocities. The trends observed between measured and predicted air velocities, especially in trial 3 after the material was turned, were very similar to trends in

compost temperature and that is the strongest indication that natural convection was the primary aeration mechanism.

4. Results indicate that compost aeration by natural convection is a more complex phenomenon than simple Darcian flow. Accumulation of carbon dioxide affects the density of compost gas while temperature increases reduces the density of the interstitial gas. Flow by natural convection only proceeds once the compost gas density is less than the ambient gas.
5. Placing a pipe at the base of a compost pile or windrow may serve as a vent for carbon dioxide gas that builds up from aerobic respiration. The strongest indication came from observing smoke flow into and out of the inlet of the chamber at the time oxygen deficits in the compost were measured during trial 3, after the material was turned, and trial 4. Carbon dioxide build up was the only explanation since compost temperatures were higher than inlet temperatures suggesting that airflow should occur only into the inlet of the chamber.
6. Air velocities predicted to maintain temperatures based on process kinetics were the closest to measured air velocity but only during periods where the process was observed to be at near steady state (after day 13). The process kinetics model assumes air exiting the compost was at saturation and was the same temperature as highest temperature in the composting media. The height where maximum temperature was recorded was used as the process temperature to model airflow.

The air at that height was assumed to be at saturation. Based on the relatively small magnitude of air velocities associated with this system, these assumptions proved to be acceptable.

7. Air velocities predicted to account for the reduction in moisture measured in trial 4 underestimated actual air velocities measured as was expected based on literature by Epstein (1997) and Haug (1993). As with the process kinetic based model, the moisture removal predictions applied only during steady state conditions.
8. A very simplified stoichiometric equation based on respiration was developed to compare O_2 and CO_2 contents based on a time dependent estimate of carbon consumed during the compost process. Predicted O_2 contents were reasonably close to the average O_2 contents measured during the O_2 deficit of trial 4. A more accurate stoichiometric balance would require that the specific chemical composition of the compost mixture be known which was not tested in this study.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Now that a methodology has been developed which allows for the continuous monitoring of airflow through a passively aerated composting media, more statistically based research should be conducted. Manufacturing another chamber so that identical mixtures could be composted simultaneously would be in order.
2. More accurate and dynamic models need to be developed that account for variations in temperature, gas content, moisture, and bulk density typical to passively and naturally aerated composting systems.
3. Further studies should be conducted on the permeability factor used in predicting air velocity using the Darcian flow based model. Developing a permeability relationship that included moisture and bulk density parameters would likely bring predicted air velocities closer to measured velocities. Once a more accurate Darcian flow based model is developed, the behavior during the periods of composting where flow was likely occurring but at undetectable rates could better be analyzed.
4. A method for measuring compost moisture content *in-situ* should be developed so that the effect moisture has on the airflow breakthrough observed in trials 3 and 4 can be studied more thoroughly. Current technologies such as moisture blocks

and TDR (time domain reflectrometry) probes were found by researchers to be adversely affected by high salt concentrations typical of most manure wastes.

5. The temperature plateau phenomena should be studied closer as this seems to be a critical point at which the composting process is starting to go anaerobic.
6. More detailed analysis of gas mixing in the inlet pipe should be conducted by continuously monitoring both oxygen and carbon dioxide contents in the inlet. In necessary, a larger diameter inlet should be used although this may reduce the air velocities to lower than detectable magnitudes. This would allow for probe placement at the top and bottom of the inlet pipe.
7. Cost analysis comparison should be made between the type of mixture used in this study (dairy manure with wood chips) and more conventional mixtures such as bedding straw and manure. The mixture used in trials 3 and 4 of this study would not be practical in most on-farm applications because screening would be necessary to remove the wood chips. But the fact that the material would likely require less turning may offset the cost of screening the material.

APPENDICIES

APPENDIX A

RAW DATA

Michigan State University - Compost Aeration Experiment: Trial #1

Andrew Fogiel

Mixture: 4 parts cow manure with bedding to 1 part leaves

Time	K T/C øC	Pt100 øC	%RH 0.9 m	CO2, ppm 0.3 m	hotwire Vel, m/s	Thermocouple Temperature Readings, deg C												
						Air center		0.3 m		0.3 m		0.3 m		0 m	0.15 m	0.6 m	0.9 m	
		Surface	height	height	Inlet		18.47	17.82	17.84	17.85	18.47	17.84	17.85	17.79	18.43	17.84	17.75	17.77
9/13/96 2:00	18.6	18.7	53.5	343	0		18.4	17.78	17.85	17.85	18.43	17.81	17.79	18.43	17.71	17.7	17.7	17.71
9/13/96 2:15	18.6	18.6	53.4	343	0		18.42	17.84	17.91	17.82	18.43	17.87	17.82	18.43	17.73	17.73	17.73	17.74
9/13/96 2:30	18.6	18.6	53.5	343	0		18.42	17.87	17.95	17.85	18.45	17.91	17.85	18.45	17.77	17.77	17.77	17.79
9/13/96 2:45	18.6	18.6	53.5	343	0		18.42	19.55	19	18.8	19.26	23.98	18.8	19.26	18.44	18.44	18.44	18.72
9/13/96 3:00	18.6	18.6	53.5	344	0		18.41	28.68	22.16	21.06	19.86	27.1	21.06	19.86	18.79	18.79	18.79	19.2
9/13/96 3:15	18.6	18.6	53.5	567	0		18.44	28.79	23.28	21.69	20.08	27.69	21.69	20.08	22.43	22.43	22.43	19.41
9/13/96 3:30	18.5	18.6	53.5	598	0		18.23	29	23.57	22.08	20.31	28.15	22.08	20.31	26.38	26.38	26.38	19.47
9/13/96 3:45	18.5	18.6	53.5	623	0		18.16	29.38	23.56	22.11	20.5	28.59	22.11	20.5	27.17	27.17	27.17	23.5
9/13/96 4:00	18.5	18.6	53.5	657	0		18.23	29.81	23.45	21.96	20.6	28.97	21.96	20.6	28.6	28.6	28.6	26.08
9/13/96 4:15	18.5	19.0	65.4	697	0		18.16	30.25	23.28	21.89	20.68	29.35	21.89	20.68	26.41	26.41	26.41	26.69
9/13/96 4:30	18.4	19.0	72.9	723	0		18.21	30.68	23.36	22.16	20.74	29.69	22.16	20.74	29.15	29.15	29.15	26.69
9/13/96 4:45	18.4	18.9	86.2	745	0		17.98	31.13	23.73	22.65	20.78	30.02	22.65	20.78	29.69	29.69	29.69	27.11
9/13/96 5:00	18.3	18.9	92.7	767	0		17.84	31.59	24.09	23.05	20.83	30.36	23.05	20.83	30.2	30.2	30.2	27.53
9/13/96 5:15	18.1	19.0	96.4	825	0		17.7	32.08	24.39	23.42	20.86	30.68	23.42	20.86	30.71	30.71	30.71	27.97
9/13/96 5:30	18.1	19.2	98.1	849	0													
9/13/96 5:45	18.0	19.2	101.2	895	0		17.53	33.14	24.91	24.02	20.9	31.32	24.02	20.9	31.74	31.74	31.74	28.83
9/13/96 6:00	18.0	19.1	102.5	906	0													
9/13/96 6:15	17.9	19.1	102.7	934	0		17.36	34.19	25.35	24.55	20.97	31.97	24.55	20.97	32.79	32.79	32.79	29.69
9/13/96 6:30	17.9	19.1	103.2	985	0													
9/13/96 6:45	17.9	19.1	103.4	999	0		17.25	35.35	25.76	25.06	21.03	32.62	25.06	21.03	33.88	33.88	33.88	30.61
9/13/96 7:00	17.8	19.1	103.8	1021	0													
9/13/96 7:15	17.8	19.1	103.9	1402	0		17.18	36.59	26.17	25.55	21.1	33.3	25.55	21.1	35.02	35.02	35.02	31.58
9/13/96 7:30	17.7	19.1	104.2	1478	0													
9/13/96 7:45	17.7	19.1	104.6	1496	0													
9/13/96 8:00	17.6	19.1	104.8	1523	0		17.11	37.91	26.62	26.05	21.19	34.01	26.05	21.19	36.25	36.25	36.25	32.57
9/13/96 8:15	17.6	19.1	104.9	1567	0													
9/13/96 8:30	17.5	19.2	105.2	1599	0		16.98	39.32	27.09	26.57	21.28	34.73	26.57	21.28	37.56	37.56	37.56	33.6

9/13/96 8:45	17.5	19.1	105.7	1645	0	16.86	40.82	27.51	26.92	21.4	35.52	38.96	34.67
9/13/96 9:00	17.4	19.1	105.8	1724	0	16.86	40.82	27.51	26.92	21.4	35.52	38.96	34.67
9/13/96 9:15	17.4	19.2	105.9	1566	0	16.65	42.41	27.23	25.79	21.52	36.36	40.45	35.74
9/13/96 9:30	17.3	19.2	106.1	1431	0	16.73	44.05	27.24	25.33	21.62	37.24	42.03	36.72
9/13/96 9:45	17.3	19.2	106.2	1789	0	16.77	45.76	27.43	25.22	21.76	38.2	43.64	37.24
9/13/96 10:00	17.3	19.2	106.4	1789	0	16.83	47.52	27.72	25.28	21.93	39.26	45.05	37.27
9/13/96 10:15	17.3	19.2	106.6	1546	0	16.82	49.31	28.08	25.35	22.15	40.39	45.67	37.24
9/13/96 10:30	17.3	19.2	106.8	1823	0	16.87	51.07	28.4	25.35	22.36	41.58	45.65	37.2
9/13/96 10:45	17.3	19.2	107.0	1845	0	16.81	52.69	28.01	25	22.64	42.81	45.47	37.25
9/13/96 11:00	17.4	19.3	107.1	1867	0	16.79	53.63	27.69	24.7	22.87	44.01	45.25	37.41
9/13/96 11:15	17.4	19.4	107.4	1967	0	16.85	53.43	27.49	24.55	23.14	45.14	44.99	37.9
9/13/96 11:30	17.5	19.4	107.9	1656	0	16.8	52.84	27.25	24.37	23.38	45.94	44.74	38.75
9/13/96 11:45	17.5	19.4	109.0	1598	0	16.77	52.16	26.95	24.15	23.63	46.25	44.47	39.72
9/13/96 12:00	17.5	19.5	109.5	1788	0	16.73	51.48	26.65	23.99	23.76	46.24	44.19	40.77
9/13/96 12:15	17.5	19.5	109.8	1766	0	16.75	50.77	26.67	24.2	23.95	46.09	43.91	41.76
9/13/96 12:30	17.5	19.5	111.0	1854	0	16.92	50.11	27.6	25.38	24.27	45.92	43.58	42.63
9/13/96 12:45	17.6	19.5	112.8	1926	0	16.87	49.45	28.31	26.22	24.61	45.84	43.27	43.5
9/13/96 13:00	17.7	19.5	113.5	1876	0	16.78	48.84	28.79	26.84	24.93	45.81	42.96	44.23
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9/13/96 13:30	17.7	19.6	114.7	1976	0								
9/13/96 13:45	17.7	19.5	115.0	1887	0								
9/13/96 14:00	17.7	19.6	115.9	1678	0								
9/13/96 14:15	17.6	19.7	116.3	2090	0								
9/13/96 14:30	17.7	19.8	116.9	1945	0								
9/13/96 14:45	17.8	19.9	117.3	1844	0								
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9/13/96 15:15	17.7	19.9	118.6	2197	0								
9/13/96 15:30	17.7	19.8	118.9	2245	0								
9/13/96 15:45	17.8	19.9	119.5	2374	0								
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9/13/96 16:15	17.8	20.0	120.1	2217	0								
9/13/96 16:30	17.8	20.0	120.2	2346	0								
9/13/96 16:45	17.6	20.1	120.4	2210	0								
9/13/96 17:00	17.6	20.0	120.1	1956	0								

9/13/96 17:15	17.5	20.1	119.5	1874	0	16.79	48.26	29.15	27.3	25.2	45.78	42.65	44.85
9/13/96 17:30	17.4	20.1	121.7	2245	0								
9/13/96 17:45	17.4	20.1	122.5	2387	0	16.8	47.74	29.43	27.67	25.46	45.72	42.36	45.47
9/13/96 18:00	17.5	21.1	119.1	2214	0								
9/13/96 18:15	17.5	21.1	118.0	2121	0	16.71	47.25	29.63	27.96	25.69	45.71	42.08	45.98
9/13/96 18:30	17.5	22.0	119.3	2096	0								
9/13/96 18:45	17.5	22.2	120.5	2245	0	16.65	46.8	29.77	28.18	25.87	45.72	41.81	46.38
9/13/96 19:00	17.4	22.3	121.8	1765	0								
9/13/96 19:15	17.3	22.2	122.4	1845	0	16.62	46.38	29.88	28.35	26.06	45.74	41.55	46.73
9/13/96 19:30	17.2	22.3	122.3	1832	0								
9/13/96 19:45	17.2	22.3	122.0	2056	0	16.5	46	29.96	28.49	26.23	45.78	41.31	46.99
9/13/96 20:00	17.2	23.1	121.6	2143	0								
9/13/96 20:15	17.1	23.1	119.2	2178	0	16.49	45.65	30.01	28.59	26.37	45.82	41.07	47.22
9/13/96 20:30	17.1	22.8	119.8	1956	0								
9/13/96 20:45	17.0	23.1	120.0	1745	0	16.46	45.34	30.06	28.67	26.51	45.84	40.85	47.46
9/13/96 21:00	16.9	23.0	121.8	2194	0								
9/13/96 21:15	16.9	23.0	120.6	2232	0	16.43	45.04	30.09	28.74	26.66	45.87	40.64	47.69
9/13/96 21:30	16.8	23.1	119.6	1798	0								
9/13/96 21:45	16.7	23.2	119.7	1659	0	16.38	44.78	30.1	28.79	26.78	45.91	40.44	47.89
9/13/96 22:00	16.6	23.2	120.8	1866	0								
9/13/96 22:15	16.6	23.2	120.6	2109	0	16.34	44.54	30.11	28.83	26.9	45.95	40.25	48.07
9/13/96 22:30	16.5	23.3	120.0	2234	0								
9/13/96 22:45	16.4	23.3	122.3	2220	0	16.29	44.32	30.1	28.85	27.01	46.01	40.07	48.18
9/13/96 23:00	16.4	23.4	120.1	1987	0								
9/13/96 23:15	16.4	23.5	117.8	1956	0	16.21	44.12	30.09	28.87	27.12	46.08	39.89	48.26
9/13/96 23:30	16.4	23.5	119.5	1689	0								
9/13/96 23:45	16.3	23.6	120.1	2345	0	16.07	43.95	30.07	28.87	27.21	46.19	39.71	48.25
9/14/96 0:00	16.3	23.6	120.1	2322	0								
9/14/96 0:15	16.2	23.7	120.1	2109	0	16.02	43.79	30.04	28.86	27.28	46.29	39.55	48.25
9/14/96 0:30	16.2	23.7	120.3	2007	0								
9/14/96 0:45	16.1	23.7	120.1	1956	0	16.01	43.65	30.02	28.85	27.36	46.4	39.41	48.26
9/14/96 1:00	16.1	23.7	120.1	2287	0								
9/14/96 1:15	16.1	23.8	120.1	1697	0	15.99	43.52	30	28.85	27.45	46.47	39.26	48.32
9/14/96 1:30	16.0	23.8	120.1	1999	0								

9/14/96 1:45	16.1	23.9	120.1	2207	0	0	15.9	43.42	29.96	28.84	27.54	46.57	39.13	48.33
9/14/96 2:00	16.0	23.9	120.1	2145	0	0	0	0	0	0	0	0	0	0
9/14/96 2:15	16.0	24.0	120.3	2198	0	0	0	0	0	0	0	0	0	0
9/14/96 2:30	16.0	24.1	120.3	2186	0	0	15.81	43.33	29.93	28.82	27.62	46.69	39	48.3
9/14/96 2:45	16.0	24.2	120.1	1999	0	0	0	0	0	0	0	0	0	0
9/14/96 3:00	15.9	24.2	120.1	2005	0	0	15.76	43.24	29.89	28.8	27.68	46.82	38.86	48.26
9/14/96 3:15	15.9	24.2	120.1	2087	0	0	0	0	0	0	0	0	0	0
9/14/96 3:30	15.8	24.2	120.1	1865	0	0	15.71	43.18	29.86	28.78	27.77	46.95	38.74	48.22
9/14/96 3:45	15.9	24.2	120.1	2176	0	0	0	0	0	0	0	0	0	0
9/14/96 4:00	15.8	24.2	120.1	2143	0	0	15.65	43.13	29.83	28.77	27.85	47.08	38.62	48.18
9/14/96 4:15	15.8	24.3	120.1	2056	0	0	0	0	0	0	0	0	0	0
9/14/96 4:30	15.7	24.4	120.1	1990	0	0	15.57	43.08	29.79	28.75	27.91	47.25	38.49	48.1
9/14/96 4:45	15.6	24.5	120.1	1988	0	0	0	0	0	0	0	0	0	0
9/14/96 5:00	15.6	24.6	120.1	1965	0	0	15.5	43.05	29.75	28.72	27.98	47.44	38.37	48.02
9/14/96 5:15	15.5	24.7	120.1	1899	0	0	0	0	0	0	0	0	0	0
9/14/96 5:30	15.5	24.6	120.1	1966	0	0	15.44	43.04	29.72	28.71	28.06	47.66	38.26	47.93
9/14/96 5:45	15.5	24.6	120.1	2134	0	0	0	0	0	0	0	0	0	0
9/14/96 6:00	15.4	24.7	120.1	1978	0	0	15.41	43.04	29.69	28.69	28.13	47.91	38.14	47.83
9/14/96 6:15	15.4	24.7	120.1	1834	0	0	0	0	0	0	0	0	0	0
9/14/96 6:30	15.5	24.9	120.1	1768	0	0	15.36	43.06	29.66	28.69	28.22	48.2	38.03	47.72
9/14/96 6:45	15.4	24.9	120.2	2001	0	0	0	0	0	0	0	0	0	0
9/14/96 7:00	15.4	25.0	120.2	1945	0	0	15.34	43.09	29.63	28.68	28.3	48.53	37.93	47.59
9/14/96 7:15	15.4	25.2	120.2	2214	0	0	0	0	0	0	0	0	0	0
9/14/96 7:30	15.3	25.2	120.2	1867	0	0	15.29	43.12	29.61	28.69	28.38	48.92	37.82	47.45
9/14/96 7:45	15.3	25.2	120.2	1798	0	0	0	0	0	0	0	0	0	0
9/14/96 8:00	15.1	25.3	120.2	1768	0	0	15.26	43.25	29.59	28.7	28.46	49.42	37.71	47.29
9/14/96 8:15	15.0	25.3	120.2	2208	0	0	0	0	0	0	0	0	0	0
9/14/96 8:30	15.0	25.3	120.1	1436	0	0	15.04	43.41	29.64	28.74	28.47	50.07	37.62	47.1
9/14/96 8:45	14.9	25.3	120.1	1655	0	0	0	0	0	0	0	0	0	0
9/14/96 9:00	14.9	25.3	120.1	2156	0	0	14.84	43.69	29.8	28.88	28.34	50.94	37.52	46.87
9/14/96 9:15	14.8	25.3	120.2	2198	0	0	0	0	0	0	0	0	0	0
9/14/96 9:30	14.8	25.3	120.2	2212	0	0	14.77	44.44	30.16	29.23	28.68	51.99	37.42	46.59
9/14/96 9:45	14.7	25.4	120.2	1666	0	0	0	0	0	0	0	0	0	0
9/14/96 10:00	14.8	25.4	120.1	2300	0	0	14.67	46.01	30.85	29.96	28.77	53.19	37.31	46.25

9/14/96 10:15	14.7	25.4	120.1	2267	0	14.63	48.33	31.98	31.06	28.92	54.6	37.23	45.87
9/14/96 10:30	14.7	25.3	120.1	1798	0	14.62	51.21	33.59	32.58	29.11	56.25	37.39	45.48
9/14/96 10:45	14.7	25.4	120.1	2309	0	14.97	59.35	35.65	34.52	29.37	58.12	37.68	45.02
9/14/96 11:00	14.7	25.4	120.1	2245	0	15.64	57.27	37.97	36.77	29.74	60.12	37.99	44.63
9/14/96 11:15	14.8	25.5	120.1	2367	0	15.46							
9/14/96 11:30	14.8	25.5	120.1	2298	0	15.23							
9/14/96 11:45	14.9	25.5	120.1	2279	0	15.12							
9/14/96 12:00	14.8	25.5	120.2	2268	0	15.08							
9/14/96 12:29	14.8	21.5	127.6	3197	0	15.41	72.7	53.62	50.85	33.23	68.31	45.63	41.82
9/14/96 12:59	15.1	22.1	118.5	2659	0	15.43	73.3	55.09	52.24	33.6	68.52	46.96	41.56
9/14/96 13:29	14.9	22.6	117.7	2542	0	15.29	74	57.67	54.77	34.2	68.79	49.54	41.1
9/14/96 13:59	15.3	22.7	117.7	2519	0	15.2	74.5	60.21	57.31	34.69	68.85	52.75	40.65
9/14/96 14:29	15.1	22.8	115.7	2411	0	15.13	74.8	62.53	59.84	35.1	68.79	56.54	40.25
9/14/96 14:59	14.4	23.1	116.1	2396	0	15.1	75	64.44	62.26	35.41	68.64	60.52	39.89
9/14/96 15:29	14	23	115.8	2405	0	15.08	75	65.82	64.38	35.63	68.36	64.28	39.6
9/14/96 15:59	14	22.7	115.6	2433	0	15.08	75	66.77	66.02	35.76	68.03	67.64	39.44
9/14/96 16:29	14	22.7	116.4	2461	0	15.08	74.9	67.34	67.22	35.83	67.67	70.3	39.47
9/14/96 16:59	13.8	22.6	116.4	2490	0	15.12	74.7	67.58	68.04	35.83	67.27	72.3	39.78
9/14/96 17:29	13.9	22.5	116.7	2514	0	15.18	74.5	67.79	68.56	35.79	66.86	73.6	40.6
9/14/96 17:59	13.8	22.3	116.8	2531	0	15.21	74.3	67.71	68.88	35.7	66.43	74.5	42.03
9/14/96 18:29	13.9	22.3	116.8	2541	0	15.21	74.1	67.64	69.03	35.58	66	75	44.14
9/14/96 18:59	14.1	22.1	116.4	2557	0	15.25	73.9	67.35	69.04	35.43	65.51	75.2	46.95
9/14/96 19:29	14	22.1	116.9	2549	0	15.28	73.7	67.03	68.94	35.26	65.14	75.3	50.51
9/14/96 19:59	14.2	22.1	117.3	2573	0	15.28	73.5	66.7	68.77	35.08	64.72	75.2	54.58
9/14/96 20:29	14.2	21.9	117.3	2599	0	15.27	73.3	66.32	68.54	34.88	64.31	75.1	58.4
9/14/96 20:59	14.2	21.8	117.7	2626	0	15.24	73.2	65.9	68.27	34.66	63.9	75	62.74
9/14/96 21:29	14.3	21.8	117.9	2653	0	15.23	73	65.53	67.97	34.44	63.51	74.9	66.25
9/14/96 21:59	14.2	21.7	117.9	2669	0	15.25	72.8	64.97	67.67	34.23	63.12	74.8	69.04
9/14/96 22:29	14.1	21.5	118.1	2689	0	15.27	72.6	64.76	67.38	34.01	62.74	74.6	71
9/14/96 22:59	14.1	21.3	118.6	2746	0	15.27	72.4	64.44	67.07	33.8	62.36	74.5	72.4
9/14/96 23:29	14.1	21.1	118.5	2777	0								
9/14/96 23:59	14	21.1	118.7	2807	0								
9/15/96 0:29	14.2	21.1	118.7	2818	0								
9/15/96 0:59	14.2	21	118.7	2848	0								

9/15/96 1:29	14.1	20.9	119.3	2893	0	15.27	72.2	64.07	66.77	33.58	61.49	74.4	73.2
9/15/96 1:59	14.1	20.8	119.2	2906	0	15.26	72	63.7	66.47	33.37	61.63	74.3	73.7
9/15/96 2:29	14.1	20.8	119.7	2928	0	15.24	71.8	63.22	66.18	33.15	61.26	74.3	73.9
9/15/96 2:59	14.1	20.8	119.8	2947	0	15.25	71.6	62.84	65.9	32.96	60.89	74.3	73.9
9/15/96 3:29	14.1	21	120.1	2921	0	15.25	71.3	62.32	65.62	32.71	60.54	74.3	73.9
9/15/96 3:59	14.2	21.3	120.4	2876	0	15.25	71.1	61.82	65.35	32.5	60.18	74.2	73.8
9/15/96 4:29	14.2	22.1	120.7	2772	0	15.27	70.9	61.47	65.07	32.3	59.84	74.1	73.7
9/15/96 4:59	14.2	23	121	2667	0	15.24	70.7	61.26	64.8	32.11	59.49	74	73.6
9/15/96 5:29	14	24.5	121.5	2478	0	15.22	70.4	60.88	64.55	31.91	59.16	74	73.5
9/15/96 5:59	14	27	121.5	2181	0	15.21	70.2	60.69	64.29	31.71	58.84	73.8	73.4
9/15/96 6:29	14.1	29.3	122.2	1969	0	15.22	69.98	60.31	64.05	31.52	58.53	73.7	73.3
9/15/96 6:59	14	31.8	123.5	1794	0	15.21	69.77	59.98	63.82	31.33	58.22	73.6	73.3
9/15/96 7:29	14.1	33.2	132.2	1963	0	15.2	69.55	59.81	63.59	31.16	57.92	73.5	73.2
9/15/96 7:59	14	34	143.9	2269	0	15.16	69.35	59.49	63.39	30.99	57.64	73.3	73.1
9/15/96 8:29	14	33.7	143.9	2300	0	15.13	69.14	59.18	63.22	30.82	57.36	73.1	73.1
9/15/96 8:59	14.1	33.4	143.9	2322	0	15.15	68.94	59.01	63.04	30.65	57.09	72.9	73
9/15/96 9:29	14.5	33.1	143.9	2362	0	15.23	68.74	58.73	62.87	30.51	56.84	72.7	72.9
9/15/96 9:59	14.6	32.9	143.8	2380	0	15.34	68.56	58.53	62.69	30.39	56.6	72.26	72.8
9/15/96 10:29	14.8	32.8	143.8	2386	0	15.47	68.38	58.38	62.51	30.28	56.38	72.4	72.7
9/15/96 10:59	15	32.4	143.8	2426	0	15.59	68.2	58.25	62.33	30.2	56.17	72.2	72.6
9/15/96 11:29	15.2	32.3	143.9	2438	0	15.72	68.02	58.11	62.15	30.12	55.96	72	72.4
9/15/96 11:59	15.2	32.6	143.8	2402	0	15.81	67.86	57.99	62	30.06	55.77	71.8	72.3
9/15/96 12:29	15.6	32.4	143.7	2428	0	15.92	67.68	58	61.87	30	55.61	71.6	72.2
9/15/96 12:59	15.9	32.6	143.8	2402	0	16.04	67.52	58.01	61.74	29.95	55.44	71.5	72.1
9/15/96 13:29	15.8	32.3	143.8	2440	0	16.16	67.36	57.9	61.61	29.91	55.3	71.3	71.9
9/15/96 13:59	16.1	32.5	143.7	2420	0	16.28	67.22	57.78	61.49	29.89	55.17	71.1	71.8
9/15/96 14:29	16.1	32.5	143.7	2410	0	16.35	67.08	57.69	61.4	29.87	55.05	71	71.7
9/15/96 14:59	16.1	32.6	143.9	2402	0	16.4	66.94	57.57	61.3	29.83	54.93	70.8	71.5
9/15/96 15:29	16.1	32.2	143.9	2456	0	16.47	66.81	57.5	61.21	29.81	54.83	70.7	71.4
9/15/96 15:59	16.3	31.9	143.9	2482	0	16.54	66.7	57.33	61.13	29.79	54.74	70.6	71.2
9/15/96 16:29	16.3	31.8	143.7	2501	0	16.6	66.59	57.23	61.05	29.78	54.67	70.4	71.1
9/15/96 16:59	16.6	32.1	143.8	2470	0	16.66	66.49	57.15	60.98	29.76	54.6	70.3	70.9
9/15/96 17:29	16.6	32.2	143.9	2442	0	16.7	66.4	57.1	60.92	29.75	54.54	70.2	70.8
9/15/96 17:59	16.4	32	143.9	2479	0	16.73	66.31	56.99	60.86	29.75	54.51	70.1	70.6

9/15/96 18:29	16.4	32.3	143.9	2438	0	16.72	66.23	56.96	60.81	29.73	54.47	69.97	70.5
9/15/96 18:59	16.3	32.7	143.8	2389	0	16.7	66.14	56.94	60.76	29.72	54.44	69.88	70.3
9/15/96 19:29	16.1	33	143.8	2362	0	16.68	66.07	56.91	60.7	29.71	54.43	69.79	70.2
9/15/96 19:59	16	33.1	143.8	2353	0	16.64	66	56.93	60.64	29.69	54.41	69.71	70.1
9/15/96 20:29	15.9	32.9	143.7	2366	0	16.61	65.93	56.93	60.6	29.68	54.42	69.63	69.94

Michigan State University - Compost Aeration Experiment: Trial #1, moisture contents

Mixture: 4 parts cow manure with bedding to 1 part leaves

Date: 9/13/96

Descriptor Initial moisture content of raw material mixture

Sample	Wet Wt + (g)	Dry Wt. + (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 16 in	278	202.4	146	57.27273
16 in - 32 i	284	208.3	148.36	55.8095
32 in - 48 i	302.4	210.4	148.12	59.63184

Date: 9/16/96

Descriptor Moisture content of compost sampled during turning

Sample	Wet Wt + (g)	Dry Wt. + (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 12 in	281.8	222	146	44.03535
12 in - 24 i	276.4	217.5	148.36	46.00125
24 in - 35 i	291	221	148.12	48.99216

Michigan State University - Compost Aeration Experiment: Trial #3

Andrew Fogiel

Mixture:

1 part cow manure, 1 part wood chips

Time	Ht in	Solomat MPM-4100					CR21X																	
		deg C		%RH		m/s	Thermocouple Temperature Readings, deg C																	
		Top	Inlet	Inlet	Inlet		REF	1	2	3	4	5	6	7	8	Plen	Inlet	1 ft	2 ft	Air	Plen	Inlet	1 ft	2 ft
9/30/96 1:00	48	12.9	12.8	58	0.48	0	13	11	11.1	11.3	11.4	11.2	11.3	11.3	11.5									
9/30/96 1:30			12.9	11.6	61.8	0.3																		
9/30/96 2:00			12.7	11.2	63.5	0	12.4	12.8	12.6	12.2	12.5	13.1	12.8	12.2	12.6									
9/30/96 2:30			13.3	10.8	62.8	0																		
9/30/96 3:00			11.1	10.7	63.6	0	11.9	14	14.4	13.3	12.5	14.5	14.4	13.4	12.4			19.1	19.2				1.9	1.8
9/30/96 3:30			12.1	10.2	63.7	0																		
9/30/96 4:00			11.9	9.8	62.6	0	11.4	14.4	14.6	13.4	12.7	14.8	14.7	13.9	12.8									
9/30/96 4:30			11.6	10	63.9	0																		
9/30/96 5:00			11.5	9.8	64.8	0	11	14.7	14.8	14.2	13.1	15.1	15	14.2	13.2									
9/30/96 5:30			11.4	9.9	64.3	0																		
9/30/96 6:00	47	11.3	9.6	65.4	0	10.8	15	15.1	14.4	13.4	15.3	15.3	14.5	13.4										
9/30/96 6:30			11.2	9.6	66.1	0																		
9/30/96 7:00			11.2	9.8	66.4	0	10.6	15.2	15.3	14.7	13.7	15.5	15.5	14.7	13.7									
9/30/96 7:30			11.2	10	67.6	0																		
9/30/96 8:00			11.2	10.2	67.3	0	10.7	15.4	15.5	14.8	13.9	15.7	15.8	15	13.9									
9/30/96 8:30			11.4	10.3	68.3	0																		
9/30/96 9:00			11.5	10.7	69.4	0	10.9	15.5	15.7	15	14.1	15.8	16	15.1	14.1									
9/30/96 9:30			11.8	11.1	70.7	0																		
9/30/96 10:00			11.8	11.3	71.9	0	11.2	15.7	15.9	15.1	14.3	16	16.3	15.3	14.3									
9/30/96 10:30			11.9	11.5	72.8	0																		
9/30/96 11:00		12.1	12.3	72.6	0	11.5	15.8	16.1	15.3	14.5	16.1	16.5	15.5	14.5			19.1	18.9				1.9	2.1	
9/30/96 11:30		12.4	12.6	71.1	0																			
9/30/96 12:00		12.5	13.6	71.8	0	12.3	16	16.3	15.4	14.7	16.3	16.6	15.6	14.7										
9/30/96 12:30		13	13.5	75.2	0																			
9/30/96 13:00		13.4	13.8	76.5	0	13	16.2	16.5	15.6	14.8	16.4	16.9	15.8	14.8										
9/30/96 13:30		14	14.1	77.5	0																			
9/30/96 14:00		14.5	15.8	73.7	0	13.7	16.3	16.7	15.7	15	16.6	17	15.9	15										

9/30/96 14:30	14.8	16.2	73.7	0	15	16.5	16.9	15.8	15.1	16.8	17.2	16	15.1
9/30/96 15:00	15.4	16.3	74.5	0	15.5	16.7	17.1	15.9	15.3	17	17.4	16.1	15.3
9/30/96 15:30	16	16.6	73.4	0	15.7	16.9	17.2	16.1	15.5	17.2	17.5	16.2	15.4
9/30/96 16:00	16.5	16.8	74.4	0	16.2	17.1	17.4	16.3	15.7	17.3	17.7	16.3	15.6
9/30/96 16:30	17.1	16.8	75.1	0	16.6	17.3	17.6	16.5	16	17.5	17.9	16.5	15.9
9/30/96 17:00	17.5	17.1	76.5	0	16.9	17.5	17.9	16.7	16.4	17.7	18.1	16.7	16.2
9/30/96 17:30	17.9	17.4	75.3	0	17.1	17.7	18.1	17	16.8	17.9	18.3	16.9	16.6
9/30/96 18:00	18.5	17.7	75.7	0	17.2	18	18.4	17.2	17.2	18.1	18.5	17.1	17
9/30/96 18:30	19	17.8	75.7	0	17.4	18.2	18.7	17.5	17.7	18.4	18.8	17.4	17.5
9/30/96 19:00	19.4	18	75.3	0	17.6	18.5	19	17.8	18.2	18.6	19	17.7	17.9
9/30/96 19:30	19.7	18.1	75.4	0	17.6	18.8	19.4	18.1	18.7	18.9	19.3	17.9	18.5
9/30/96 20:00	20	18.2	73.7	0	17.7	19.1	19.7	18.5	19.2	19.1	19.6	18.3	19
9/30/96 20:30	20.2	18.3	73.2	0	17.8	19.4	20	18.8	19.8	19.4	19.9	18.6	19.5
9/30/96 21:00	20.3	18.3	72.9	0	17.9	19.8	20.4	19.2	20.4	19.7	20.2	18.9	20
9/30/96 21:30	20.3	18.3	72.6	0	17.9	20.1	20.8	19.5	20.9	20	20.6	19.2	20.6
9/30/96 22:00	20.5	18.4	72.3	0	18	20.4	21.1	19.9	21.5	20.3	20.9	19.6	21.1
9/30/96 22:30	20.5	18.4	71.8	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
9/30/96 23:00	20.5	18.6	71.5	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
9/30/96 23:29	20.7	18.1	71.1	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
9/30/96 23:59	20.7	17.9	74.1	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 0:29	20.9	17.8	74.8	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 0:59	21	17.8	75.1	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 1:29	21.2	17.8	75.3	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 1:59	21.1	17.8	75.5	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 2:29	21.2	17.8	75.7	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 2:59	21.5	17.8	75.8	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 3:29	21.4	17.8	75.9	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 3:59	21.7	17.8	76	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 4:29	21.7	17.8	76.1	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 4:59	21.7	17.8	76.1	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 5:29	21.9	17.8	76.2	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 5:59	22.1	17.8	76.3	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 6:29	22.1	17.8	76.4	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6
10/1/96 6:59	22.2	17.8	76.4	0	18	20.7	21.5	20.2	22	20.7	21.3	19.9	21.6

10/1/96 7:29	22.3	17.8	76.5	0	18	21.1	21.9	20.6	22.5	21	21.6	20.3	22.2	46	15	16.4	17.3	4	3.5	2.5			
10/1/96 7:59	22.3	17.8	76.5	0																			
10/1/96 8:29	22.3	17.8	76.6	0																			
10/1/96 8:59	22.4	17.9	76.6	0	18.1	21.5	22.2	21	23.1	21.3	22	20.6	22.7										
10/1/96 9:29	22.5	17.9	76.6	0																			
10/1/96 9:59	22.7	18.1	76.6	0	18.2	21.8	22.6	21.4	23.6	21.7	22.3	21	23.2										
10/1/96 10:29	22.7	18.2	76.6	0																			
10/1/96 10:59	22.8	18.3	76.5	0	18.5	22.2	23	21.7	24.2	22	22.7	21.4	23.7										
10/1/96 11:29	23	18.5	76.5	0																			
10/1/96 12:00	23.2	20.3	67.1	0	18.8	22.5	23.4	22.1	24.7	22.4	23.1	21.7	24.3										
10/1/96 13:00	23.5	20.4	66.4	0	19.2	22.9	23.8	22.5	25.3	22.7	23.5	22.1	24.8	45	13	16.4	12.3	13.5	20.7	6.5	3.5	8	6.5
10/1/96 14:00	23.9	20.6	64.3	0	19.4	23.3	24.2	23	25.9	23.1	23.9	22.5	25.4										
10/1/96 15:00	24.5	21	63.3	0	19.7	23.7	24.7	23.4	26.5	23.4	24.3	23	25.9										
10/1/96 16:00	24.6	21.1	63.3	0	20	24.1	25.1	23.9	27.1	23.9	24.8	23.4	26.5										
10/1/96 17:00	24.7	21.3	62.8	0	20.2	24.5	25.6	24.4	27.8	24.3	25.2	23.9	27.2										
10/1/96 18:00	24.7	21.5	63.8	0	20.5	25	26.1	24.9	28.4	24.7	25.7	24.4	27.8										
10/1/96 19:00	25.3	21.6	65.7	0	20.6	25.4	26.7	25.5	29.1	25.2	26.3	25	28.5										
10/1/96 20:00	25.6	21.6	66.3	0	20.7	25.9	27.2	26.1	29.9	25.6	26.8	25.5	29.2										
10/1/96 21:00	25.8	21.6	66.5	0	20.7	26.4	27.8	26.7	30.6	26.1	27.4	26.1	30										
10/1/96 22:00	26	21.5	67.1	0	20.8	26.9	28.4	27.3	31.4	26.6	28	26.7	30.8										
10/1/96 23:00	26	21.7	66.7	0	20.8	27.5	29	28	32.2	27.2	28.6	27.4	31.6	45	10	18.1	5.5	7	20.8	9	2.9	14.5	13
10/2/96 0:00	26.3	21.3	68.5	0	20.8	28	29.7	28.7	33	27.7	29.2	28.1	32.4										
10/2/96 1:00	26.7	21.3	68.7	0	20.7	28.6	30.3	29.4	33.8	28.3	29.9	28.8	33.1										
10/2/96 2:00	27.1	21.3	69.3	0	20.8	29.2	31	30.2	34.7	28.9	30.6	29.5	34										
10/2/96 3:00	27.1	21.5	69.3	0	20.8	29.7	31.7	30.9	35.5	29.4	31.3	30.3	34.8										
10/2/96 4:00	27	21.2	70.7	0	20.8	30.3	32.4	31.7	36.4	30	32.1	31.1	35.7										
10/2/96 5:00	27.1	21.1	71.9	0	20.8	30.9	33.2	32.5	37.3	30.6	32.8	31.9	36.5										
10/2/96 6:00	27.4	21.2	71.8	0	20.7	31.6	33.9	33.4	38.1	31.3	33.6	32.8	37.4										
10/2/96 7:00	28	21.3	71.2	0	20.8	32.2	34.7	34.3	39	31.9	34.4	33.7	38.3										
10/2/96 8:00	28.2	21.3	70.9	0	20.8	32.9	35.5	35.2	39.9	32.6	35.3	34.6	39.2										
10/2/96 9:00	28.7	21.5	70.7	0	20.9	33.5	36.4	36.2	40.7	33.2	36.2	35.5	40										
10/2/96 10:00	29	21.5	71.2	0	21	34.2	37.2	37.2	41.6	33.9	37.1	36.5	40.9	45	7	20.8	9	2.9	14.5	13			
10/2/96 11:00	29.4	21.6	71.1	0	21	34.9	38.1	38.2	42.5	34.6	38	37.6	41.7										
10/2/96 12:00	26.6	22.5	67.7	0	21.1	35.6	38.9	39.2	43.3	35.3	38.9	38.6	42.6										

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10/3/96 23:00	43	40.6	17.3	36.7	0	17.3	27.1	34	44.2	51.3	26.4	34.5	44.1	50.1	20	20.4	20.4	19.8	20.9
10/4/96 0:00		36.8	17.3	34.2	0	17.5	26.9	33.6	43.9	50.3	26.7	34.1	43.8	49.3					
10/4/96 1:00		36.4	16.9	33.8	0														
10/4/96 2:00		36.3	17.2	35.5	0														
10/4/96 3:00		36.2	17.3	35.1	0	17.1	26.8	32.9	43	49	26.8	33.3	42.6	47.9					
10/4/96 4:00		36.2	17.3	35.3	0														
10/4/96 5:00		36.2	17.1	35.7	0														
10/4/96 6:00		36.3	17.1	34.3	0	16.9	27.1	33	42.6	48.7	26.9	33.6	42.1	48					
10/4/96 7:00		36.2	17	34.3	0														
10/4/96 8:00		36.2	16.7	33.1	0														
10/4/96 9:00		36.1	16.8	34.8	0	16.7	27.4	33.3	42.4	48.3	27.1	33.9	41.9	47.8					
10/4/96 10:00		35.9	17.1	36.6	0														
10/4/96 11:00		35.6	17.2	36.7	0														
10/4/96 12:00		35.5	17.5	37.1	0	16.9	27.7	33.6	42.3	47.8	27.3	34.2	41.9	47.4					
10/4/96 13:00		35.6	17.8	36.9	0														
10/4/96 14:00		35.4	18.2	36.5	0														
10/4/96 15:00		35.5	18.6	36.7	0	17.7	28.1	34.1	42.5	47.4	27.7	34.8	42	47.2					
10/4/96 16:00		35.3	18.8	35.4	0														
10/4/96 17:00		35.1	19	35.4	0														
10/4/96 18:00		35.1	19.1	36.1	0	18.3	28.6	34.7	42.9	47.3	28.2	35.4	42.4	47.2					
10/4/96 19:00		35	19.3	36.2	0														
10/4/96 20:00		35.1	19.3	37.2	0														
10/4/96 21:00		34.7	18.7	32.4	0	18.5	29.2	35.5	43.6	47.6	28.8	36.2	43	47.6					
10/4/96 22:00		34.3	18.4	35.5	0														
10/4/96 23:00	43	34.3	18.4	36.5	0										20	20.3	19	18.2	21.2
10/5/96 0:00		34.4	18.2	37.2	0	18.1	29.7	36.2	44.4	48.2	29.2	36.8	43.8	48.3					
10/5/96 1:00		34.3	18.1	37.7	0														
10/5/96 2:00		34.5	17.9	38.3	0														
10/5/96 3:00		34.4	17.7	38.9	0	17.8	30.2	36.8	45.3	48.9	29.6	37.5	44.8	49.1					
10/5/96 4:00		34.4	17.3	39.9	0														
10/5/96 5:00		34.5	17.5	39.1	0														
10/5/96 6:00		34.5	17.2	39.5	0	17.4	30.5	37.3	46.2	49.6	29.9	38.2	45.8	49.9					
10/5/96 7:00		34.8	17.2	39.2	0														
10/5/96 8:00		34.8	17	39	0														

10/5/96 9:00	34.7	17.2	40.6	0	17.2	30.8	37.8	47.2	50.5	30.2	38.7	46.8	50.9
10/5/96 10:00	34.7	17.6	39.2	0									
10/5/96 11:00	34.5	17.8	38.5	0									
10/5/96 12:00	34.7	18	38.4	0	17.3	31.1	38.3	48.2	51.3	30.5	39.4	47.8	51.7
10/5/96 13:00	35	18.5	37.9	0									
10/5/96 14:00	35.3	18.8	36.9	0									
10/5/96 15:00	35.8	19.2	33.8	0	18.2	31.4	38.9	49.4	52.1	30.9	40.1	49.2	52.5
10/5/96 16:00	36.1	19.6	33.1	0									
10/5/96 17:00	36.3	19.8	33.6	0									
10/5/96 18:00	36.7	19.8	32.2	0	18.9	31.9	39.7	50.7	52.9	31.4	40.9	50.6	53.3
10/5/96 19:00	37	20	34.7	0									
10/5/96 20:00	37.1	19.6	32.1	0									
10/5/96 21:00	37.2	19.4	32.7	0	19	32.5	40.5	51.9	53.9	31.8	41.7	51.9	54.3
10/5/96 22:00	37.5	18.8	34.5	0									
10/5/96 23:00	37.9	18.7	37.8	0									
10/6/96 0:00	38.2	18.6	41	0	18.6	32.9	41.2	52.8	54.6	32.1	42.4	52.8	55
10/6/96 1:00	38.6	18.6	43.4	0									
10/6/96 2:00	39.2	18.6	43.5	0									
10/6/96 3:00	39.4	18.5	43.1	0	18.5	33.3	41.8	53.3	55	32.5	43	53.4	55.3
10/6/96 4:00	39.7	18.5	42.1	0									
10/6/96 5:00	39.8	18.1	42.2	0									
10/6/96 6:00	40	18.1	42	0	18.2	33.6	42.4	53.7	55.1	32.9	43.8	53.8	55.4
10/6/96 7:00	40.1	17.9	42.4	0									
10/6/96 8:00	40.1	17.8	43.2	0									
10/6/96 9:00	39.9	18.2	44.3	0	18.1	33.8	42.6	53.7	55.1	33	44	53.9	55.3
10/6/96 10:00	40.1	18.7	47.1	0									
10/6/96 11:00	40.1	19.1	50.7	0									
10/6/96 12:00	40.1	19.5	56.4	0	18.5	34.5	43.5	53.9	54.6	33.7	45	54.1	54.9
10/6/96 13:00	40.2	20	63.3	0									
10/6/96 14:00	40.3	20.4	66.1	0									
10/6/96 15:00	40.3	20.8	67.3	0	19.5	35.2	44.4	54.2	54.2	34.3	45.8	54.3	54.5
10/6/96 16:00	40.5	21.1	66.2	0									
10/6/96 17:00	40.5	21.3	64.8	0	20.4	36.1	45.4	54.5	54	35.2	46.7	54.7	54.4
10/6/96 18:00	40.3	21.5	63	0									

10/6/96 19:00	40.4	21.5	61.1	0	0	36.9	46.4	54.9	54.1	36	47.6	55.1	54.5	20	20.1	17.9	16.2	20.5	2.5	4
10/6/96 20:00	40.5	21.3	59.5	0	0	20.5	36.9	46.4	54.9	54.1	36	47.6	55.1	54.5	20	20.1	17.9	16.2	20.5	2.5
10/6/96 21:00	40.5	21.1	59.2	0	0	20.5	36.9	46.4	54.9	54.1	36	47.6	55.1	54.5	20	20.1	17.9	16.2	20.5	2.5
10/6/96 22:00	40.5	20.9	58	0	0	20.5	36.9	46.4	54.9	54.1	36	47.6	55.1	54.5	20	20.1	17.9	16.2	20.5	2.5
10/6/96 23:00	40.5	20.8	56.5	0	0	20.3	37.8	47.3	55.2	54.2	36.8	48.5	55.3	54.7	20	20.1	17.9	16.2	20.5	2.5
10/7/96 0:00	41	20.5	57.4	0	0	20.3	37.8	47.3	55.2	54.2	36.8	48.5	55.3	54.7	20	20.1	17.9	16.2	20.5	2.5
10/7/96 1:00	41.3	20.3	59.6	0	0	20.3	37.8	47.3	55.2	54.2	36.8	48.5	55.3	54.7	20	20.1	17.9	16.2	20.5	2.5
10/7/96 2:00	41.4	20.2	60.9	0	0	20.1	38.6	48	55.3	54	37.6	49.2	55.5	54.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 3:00	41.4	20.2	59.9	0	0	20.1	38.6	48	55.3	54	37.6	49.2	55.5	54.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 4:00	41.3	20.1	60.1	0	0	20.1	38.6	48	55.3	54	37.6	49.2	55.5	54.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 5:00	41.3	20.1	60	0	0	20.1	38.6	48	55.3	54	37.6	49.2	55.5	54.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 6:00	41.2	20	59.7	0	0	20	39.3	48.7	55.3	53.6	38.4	49.8	55.5	54.4	20	20.1	17.9	16.2	20.5	2.5
10/7/96 7:00	41.2	20	59.2	0	0	20	39.3	48.7	55.3	53.6	38.4	49.8	55.5	54.4	20	20.1	17.9	16.2	20.5	2.5
10/7/96 8:00	41.4	19.7	58.8	0	0	19.8	40	49.3	55.2	53.3	39.1	50.4	55.4	54	20	20.1	17.9	16.2	20.5	2.5
10/7/96 9:00	41.4	20.4	58.3	0	0	19.8	40	49.3	55.2	53.3	39.1	50.4	55.4	54	20	20.1	17.9	16.2	20.5	2.5
10/7/96 10:00	41.4	20.3	60.1	0	0	19.8	40	49.3	55.2	53.3	39.1	50.4	55.4	54	20	20.1	17.9	16.2	20.5	2.5
10/7/96 11:00	41.2	20.8	59.9	0	0	19.8	40	49.3	55.2	53.3	39.1	50.4	55.4	54	20	20.1	17.9	16.2	20.5	2.5
10/7/96 12:00	40.9	21	60.9	0	0	20.4	40.7	49.9	55	52.8	39.9	50.9	55.3	53.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 13:00	40.7	20	62.8	0	0	20.4	40.7	49.9	55	52.8	39.9	50.9	55.3	53.6	20	20.1	17.9	16.2	20.5	2.5
10/7/96 14:00	40.4	19.7	60.5	0	0	19.8	41.4	50.4	55	52.5	40.5	51.4	55.2	53.2	20	20.1	17.9	16.2	20.5	2.5
10/7/96 15:00	40.1	19.3	61.3	0	0	19.8	41.4	50.4	55	52.5	40.5	51.4	55.2	53.2	20	20.1	17.9	16.2	20.5	2.5
10/7/96 16:00	39.8	19.3	60.1	0	0	19.8	41.4	50.4	55	52.5	40.5	51.4	55.2	53.2	20	20.1	17.9	16.2	20.5	2.5
10/7/96 17:00	39.6	19.1	58.1	0	0	19.4	42	50.8	54.9	52.1	41.1	51.8	55.1	52.8	20	20.1	17.9	16.2	20.5	2.5
10/7/96 18:00	39.3	19	57.8	0	0	19.4	42	50.8	54.9	52.1	41.1	51.8	55.1	52.8	20	20.1	17.9	16.2	20.5	2.5
10/7/96 19:00	39	18.9	56.4	0	0	19.4	42	50.8	54.9	52.1	41.1	51.8	55.1	52.8	20	20.1	17.9	16.2	20.5	2.5
10/7/96 20:00	38.6	18.6	55.5	0	0	19	42.5	51.1	54.7	51.5	41.6	52.1	54.9	52.3	20	20.1	17.9	16.2	20.5	2.5
10/7/96 21:00	38.1	18.4	55.3	0	0	19	42.5	51.1	54.7	51.5	41.6	52.1	54.9	52.3	20	20.1	17.9	16.2	20.5	2.5
10/7/96 22:00	37.8	18.4	54.8	0	0	19	42.5	51.1	54.7	51.5	41.6	52.1	54.9	52.3	20	20.1	17.9	16.2	20.5	2.5
10/7/96 23:00	37.2	18.2	53.9	0	0	18.3	42.9	51.3	54.2	51	42.1	52.3	54.7	51.7	19	20	17.1	15.8	20.4	4.9
10/8/96 0:00	36.8	17.8	54.1	0	0	18.3	42.9	51.3	54.2	51	42.1	52.3	54.7	51.7	19	20	17.1	15.8	20.4	4.9
10/8/96 1:00	36.5	17.9	53.7	0	0	18.3	42.9	51.3	54.2	51	42.1	52.3	54.7	51.7	19	20	17.1	15.8	20.4	4.9
10/8/96 2:00	36.1	17.8	52.4	0	0	18.2	43.2	51.4	53.9	50.2	42.4	52.3	54.4	51	19	20	17.1	15.8	20.4	4.9
10/8/96 3:00	35.8	17.8	52.1	0	0	18.2	43.2	51.4	53.9	50.2	42.4	52.3	54.4	51	19	20	17.1	15.8	20.4	4.9
10/8/96 4:00	35.5	17.9	51.1	0	0	18.2	43.2	51.4	53.9	50.2	42.4	52.3	54.4	51	19	20	17.1	15.8	20.4	4.9

10/8/96 5:00	35.1	18	51.6	0	18.1	43.5	51.4	53.5	49.4	42.7	52.3	54.1	50.2
10/8/96 6:00	34.8	17.7	52	0									
10/8/96 7:00	34.5	17.8	52.1	0									
10/8/96 8:00	34.2	17.8	53.3	0									
10/8/96 9:00	34	17.6	52.7	0	17.9	43.7	51.4	53.3	48.7	42.9	52.3	53.7	49.8
10/8/96 10:00	33.7	17.7	52.6	0									
10/8/96 11:00	33.4	17.5	53.1	0									
10/8/96 12:00	33.2	17.3	51.2	0	17.7	43.9	51.3	52.8	48	43.2	52.2	53.3	48.7
10/8/96 13:00	33	17.2	51.6	0									
10/8/96 14:00	32.8	17.6	51.6	0									
10/8/96 15:00	32.9	15.5	58.3	0	17.5	44.1	51.2	52.4	47.3	43.3	52.1	52.9	48
10/8/96 16:00	32.4	16.6	55.9	0									
10/8/96 17:00	32.4	16.8	54.8	0									
10/8/96 18:00	32.2	16.7	54.4	0	17.1	44.2	51	51.8	46.6	43.4	51.8	52.5	47.3
10/8/96 19:00	32	16.6	54.4	0									
10/8/96 20:00	31.8	16.6	52.6	0									
10/8/96 21:00	31.6	16.7	52.2	0	16.8	44.2	50.8	51.3	45.9	43.5	51.3	52	46.6
10/8/96 22:00	31.3	16.6	52.1	0									
10/8/96 23:00	31.1	16.6	52.2	0									
10/9/96 0:00	30.9	16.5	52.2	0	16.7	44.2	50.5	50.8	45.2	43.5	51.2	51.5	46
10/9/96 1:00	30.7	16.3	52.6	0									
10/9/96 2:00	30.6	16.4	53	0									
10/9/96 3:00	30.4	16.2	52.9	0	16.6	44.1	50.2	50.4	44.5	43.5	50.9	51	45.3
10/9/96 4:00	30.1	16.1	52.4	0									
10/9/96 5:00	29.9	16	51.8	0									
10/9/96 6:00	29.7	15.8	50.8	0	16.3	43.9	49.8	49.9	43.8	43.3	50.5	50.4	44.6
10/9/96 7:00	29.4	16	49.9	0									
10/9/96 8:00	29.3	15.8	49.6	0									
10/9/96 9:00	29.3	16.1	51.2	0	16	43.6	49.3	49.3	43.1	43	50	49.9	43.9
10/9/96 10:00	29.1	16.1	52.3	0									
10/9/96 11:00	28.9	16.2	52.4	0									
10/9/96 12:00	28.6	16.3	51.1	0	16.4	43.3	48.8	48.7	42.4	42.7	49.4	49.2	43.1
10/9/96 13:00	28.4	16.5	49.7	0									
10/9/96 14:00	28.2	17	47.4	0									

10/12/96 10:59	23.8	18.2	51.1	0	17.5	29.4	32	33	28.1	29	32.2	32.8	28.2
10/12/96 11:59	23.9	18.5	52.4	0									
10/12/96 12:59	24.1	18.7	52.9	0									
10/12/96 13:59	24.2	19	53.1	0									
10/12/96 14:59	24.4	19.4	54.2	0	18.1	29.1	31.6	32.5	27.9	28.6	31.6	32.2	27.9
10/12/96 15:59	24.6	19.7	57.9	0									
10/12/96 16:59	24.7	20	59.3	0									
10/12/96 17:59	24.9	20.2	59.9	0	18.9	28.8	31.2	32	27.9	28.4	31.2	31.7	27.7
10/12/96 18:59	25	20.2	60	0									
10/12/96 19:59	25	20.4	59.5	0									
10/12/96 20:59	25.1	20.6	60.3	0	19.4	28.7	31	31.6	27.8	28.3	30.8	31.3	27.7
10/12/96 21:59	25	20.6	59.4	0									
10/12/96 22:59	25	20.6	59.4	0									
10/12/96 23:59	25	20.6	58.1	0	19.7	28.8	30.8	31.4	27.8	28.2	30.6	31	27.7
10/13/96 0:59	25	20.6	57.6	0									
10/13/96 1:59	24.9	20.6	57	0									
10/13/96 2:59	24.9	20.6	56.4	0	19.9	28.8	30.8	31.1	27.8	28.3	30.5	30.7	27.7
10/13/96 3:59	24.9	20.6	55.8	0									
10/13/96 4:59	24.8	20.6	55.4	0									
10/13/96 5:59	24.8	20.6	55	0	20	28.9	30.7	31	27.6	28.4	30.4	30.5	27.6
10/13/96 6:59	24.7	20.6	54.9	0									
10/13/96 7:59	24.7	20.5	55.4	0									
10/13/96 8:59	24.8	20.6	55	0	20.1	29	30.7	30.8	27.6	28.5	30.4	30.4	27.5
10/13/96 9:59	24.7	20.7	55.3	0									
10/13/96 10:59	24.7	21.1	56.2	0									
10/13/96 11:59	24.9	21.3	59	0	20.3	29.1	30.7	30.7	27.5	28.6	30.4	30.3	27.4
10/13/96 12:59	25.1	21.7	60.1	0									
10/13/96 13:59	25.3	22	59.9	0									
10/13/96 14:59	25.4	22.2	59.2	0	21	29.2	30.7	30.6	27.4	28.7	30.4	30.2	27.5
10/13/96 15:59	25.3	22.3	59	0									
10/13/96 16:59	25	22.3	59.6	0									
10/13/96 17:59	24.7	22.3	60.1	0	21.7	29.4	30.8	30.5	27.5	28.9	30.4	30.1	27.5
10/13/96 18:59	24.7	22.3	60.1	0									
10/13/96 19:59	24.6	22.3	60.7	0									

10/13/96 20:59	24.5	22.3	60.7	0	21.9	29.6	30.9	30.5	27.5	29.2	30.6	30.1	27.5
10/13/96 21:59	24.7	22.3	61	0									
10/13/96 22:59	24.8	22.4	61.5	0									
10/13/96 23:59	24.6	22.2	61.2	0	22	29.9	31.1	30.6	27.5	29.4	30.7	30.2	27.4
10/14/96 0:59	24.4	22	61.1	0									
10/14/96 1:59	24.2	21.6	59.6	0									
10/14/96 2:59	24	21.2	56.9	0	21.7	30.2	31.3	30.7	27.5	29.7	31	30.3	27.4
10/14/96 3:59	23.7	21	53.8	0									
10/14/96 4:59	23.5	20.7	50.4	0									
10/14/96 5:59	23.4	20.5	48.9	0	21.1	30.4	31.5	30.7	27.3	30	31.2	30.4	27.3
10/14/96 6:59	23.4	20.3	48.8	0									
10/14/96 7:59	23.1	20	48.2	0									
10/14/96 8:59	23.1	20	48.4	0	20.4	30.5	31.6	30.7	27.1	30.1	31.4	30.5	27.2
10/14/96 9:59	23.1	20.7	49.6	0									
10/14/96 10:59	22.8	20.8	48.3	0									
10/14/96 11:59	22.7	21	47	0	20.6	30.6	31.7	30.7	26.9	30.2	31.5	30.5	26.8
10/14/96 12:59	22.9	21.1	47.5	0									
10/14/96 13:59	22.8	21.2	45.8	0									
10/14/96 14:59	22.9	21.4	44.1	0	21.1	30.5	31.7	30.7	26.7	30.2	31.5	30.5	26.7
10/14/96 15:59	23.1	21.6	45.2	0									
10/14/96 16:59	23.2	21.6	45	0									
10/14/96 17:59	23.1	21.3	44.1	0	21.5	30.5	31.7	30.6	26.6	30.1	31.5	30.4	26.5
10/14/96 18:59	22.9	20.8	42.4	0									
10/14/96 19:59	22.6	20.5	41.9	0									
10/14/96 20:59	22.3	20.2	42	0	21	30.5	31.7	30.6	26.5	30.1	31.5	30.4	26.5
10/14/96 21:59	22.1	20	41.7	0									
10/14/96 22:59	21.8	19.8	41.7	0									
10/14/96 23:59	21.6	19.5	41.5	0	20.4	30.4	31.7	30.6	26.3	30.1	31.6	30.5	26.3
10/15/96 0:59	21.5	19.3	41.7	0									
10/15/96 1:59	21.4	19.1	42.6	0									
10/15/96 2:59	21.2	19	43.1	0	19.9	30.3	31.6	30.5	26	30	31.5	30.4	26
10/15/96 3:59	21.2	18.6	42.9	0									
10/15/96 4:59	21	18.4	42.9	0									
10/15/96 5:59	20.9	18.3	43	0	19.3	30.1	31.4	30.4	25.7	29.8	31.4	30.3	25.7

[illegible]

10/17/96 10:59	23.1	21.7	68.1	0	20.3	26.1	25.2	28.1	23.5	26.1	25.2	28.4	22.9
10/17/96 11:29	23.2	21.8	69.4	0									
10/17/96 11:59	23.3	21.9	69.4	0	20.4	26.5	25.6	28.4	23.5	26.4	25.6	28.7	22.9
10/17/96 12:29	23.4	22	69.3	0									
10/17/96 12:59	23.4	22	67.6	0	20.6	26.8	25.9	28.9	23.9	26.7	26	29.2	23.5
10/17/96 13:29	23.3	22.1	66.4	0									
10/17/96 13:59	23.6	22.2	65.8	0	20.8	27.2	26.3	29.3	24	27.1	26.4	29.7	23.9
10/17/96 14:29	23.7	22.3	66.2	0									
10/17/96 14:59	23.5	22.4	65.3	0	21	27.5	26.8	29.8	24.2	27.4	26.8	30.2	24.1
10/17/96 15:29	23.5	22.4	64.3	0									
10/17/96 15:59	23.9	22.5	62.6	0	21.2	27.9	27.2	30.4	24.3	27.8	27.3	30.7	24.2
10/17/96 16:29	24.1	22.6	63.9	0									
10/17/96 16:59	24.3	22.6	63.2	0	21.4	28.3	27.6	30.9	24.5	28.2	27.7	31.2	24
10/17/96 17:29	24.3	22.7	63.2	0									
10/17/96 17:59	24.3	22.7	64	0	21.5	28.7	28.1	31.5	24.7	28.5	28.2	31.8	24
10/17/96 18:29	24.1	22.7	65	0									
10/17/96 18:59	23.9	22.7	63.8	0	21.5	29	28.5	32	24.6	28.9	28.6	32.4	24.4
10/17/96 19:29	24.1	22.7	63.7	0									
10/17/96 19:59	24.1	22.7	64.9	0	21.6	29.4	29	32.6	24.4	29.3	29.1	33	24.3
10/17/96 20:29	24.2	22.8	66.3	0									
10/17/96 20:59	24.1	22.7	65.8	0	21.6	29.8	29.5	33.2	24.6	29.7	29.6	33.6	24.2
10/17/96 21:29	23.8	22.7	64.5	0									
10/17/96 21:59	24.2	22.7	64.1	0	21.6	30.2	30	33.8	24.4	30.1	30.1	34.2	24.2
10/17/96 22:29	24.2	22.7	66.6	0									
10/17/96 22:59	22.3	22.8	64.6	0	21.6	30.6	30.5	34.4	24.4	30.4	30.6	34.8	24
10/17/96 23:29	21.5	22.3	68	0									
10/17/96 23:59	22.7	22.3	67.2	0	21.6	31	31	35	24.1	30.8	31.1	35.4	23.9
10/18/96 0:29	23.8	22.4	67.6	0									
10/18/96 0:59	23	22.5	68.4	0	21.5	31.4	31.4	35.6	24.6	31.1	31.6	36	24.1
10/18/96 1:29	22.4	22.6	68.5	0									
10/18/96 1:59	22.7	22.5	67.9	0	21.5	31.7	31.9	36.2	24.1	31.5	32.1	36.6	24
10/18/96 2:29	22.1	22.3	62.3	0									
10/18/96 2:59	22	22.2	61.2	0	21.3	32.1	32.4	36.8	23.5	31.8	32.6	37.3	23.6
10/18/96 3:29	22.2	22.1	62	0									

10/18/96 3:59	21.9	21.5	55.2	0	21.2	32.3	32.8	37.4	23.1	32	33	37.8	23.2
10/18/96 4:29	21.3	21.1	53.2	0									
10/18/96 4:59	21.6	21	52	0	20.8	32.5	33.1	37.9	22.4	32.1	33.3	38.3	22.5
10/18/96 5:29	21	20.9	50.7	0									
10/18/96 5:59	21	20.8	50.4	0	20.5	32.6	33.3	38.3	22.2	32.2	33.4	38.8	22.2
10/18/96 6:29	21.2	21	50.8	0									
10/18/96 6:59	27.3	20	52.4	0	20.5	32.7	33.5	38.8	22.4	32.2	33.6	39.3	22.1
10/18/96 7:29	26.2	20.3	48	0									
10/18/96 7:59	26.1	20.5	47.2	0	20.2	32.9	33.7	39.3	22.1	32.3	33.8	39.7	22
10/18/96 8:29	26	20.2	45.5	0									
10/18/96 8:59	26	20.7	45.6	0	20.1	33	33.9	39.7	22	32.4	33.8	40.1	21.7
10/18/96 9:29	26.2	21	45.8	0									
10/18/96 9:59	26.1	20.9	47.4	0	20.2	33.1	34.1	40.1	22.5	32.4	34	40.5	22
10/18/96 10:29	26.2	20.7	45.1	0									
10/18/96 10:59	26.2	20.8	44.2	0	20.2	33.2	34.3	40.5	22.4	32.5	34.3	41	22
10/18/96 11:29	26.3	20.9	46.1	0									
10/18/96 11:59	26.4	20.8	46	0	20.1	33.4	34.5	40.9	22.6	32.6	34.4	41.4	22.1
10/18/96 12:29	26.3	20.5	42.2	0									
10/18/96 12:59	26.2	20.6	41.5	0	20	33.5	34.7	41.3	22.2	32.8	34.5	41.7	22
10/18/96 13:29	26.2	20.6	40.9	0									
10/18/96 13:59	26.1	20.1	38.5	0	19.9	33.8	34.8	41.6	22	32.9	34.6	42	21.8
10/18/96 14:29	26.1	19.7	38.5	0									
10/18/96 14:59	26.1	20.2	39.3	0	19.6	34	35	41.8	21.5	33.2	34.6	42.2	21.4
10/18/96 15:29	26	20.1	38.7	0									
10/18/96 15:59	26.1	20	38	0	19.6	34.4	35.2	42	21.7	33.3	34.6	42.4	21.5
10/18/96 16:29	26.1	19.8	38.6	0									
10/18/96 16:59	26.1	19.7	38.3	0	19.5	34.6	35.5	42.1	21.5	33.5	34.7	42.5	21.4
10/18/96 17:29	26.1	19.8	37.1	0									
10/18/96 17:59	26.1	19.7	37.2	0	19.4	35	35.8	42.2	21.4	33.6	34.7	42.7	21.3
10/18/96 18:29	26.1	19.6	37.3	0									
10/18/96 18:59	26.1	19.7	37.6	0	19.3	35.3	36.1	42.3	21.3	33.8	34.8	42.8	21.2
10/18/96 19:29	26.1	19.7	37	0									
10/18/96 19:59	26.1	19.7	37.4	0	19.3	35.6	36.4	42.3	21.4	34	34.9	42.8	21.3
10/18/96 20:29	26.2	19.5	37.8	0									

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10/18/96 20:59	26.2	19.6	37.2	0	19.2	35.9	36.8	42.4	21.3	34.2	34.9	42.9	21.2
10/18/96 21:29	26.2	19.7	37.5	0									
10/18/96 21:59	26.5	19.7	37.4	0	19.2	36.3	37.1	42.4	21.5	34.4		42.9	21.3
10/18/96 22:29	26.5	19.6	36.9	0									
10/18/96 22:59	26.5	19.6	36	0	19.2	36.6	37.5	42.6	21.6	34.6		42.9	21.3
10/18/96 23:29	26.5	19.5	35.7	0									
10/18/96 23:59	26.7	19.5	35.6	0	19	37	38	42.8	21.7	34.9		42.9	21.4
10/19/96 0:29	27.2	19.4	36.2	0									
10/19/96 0:59	27.7	19.4	36.3	0	19	37.4	38.4	43	22.5	35.3		42.9	22.1
10/19/96 1:29	28.6	19.4	36.2	0									
10/19/96 1:59	29.1	19.4	36.8	0	18.9	37.8	39	43.3	24.8	35.8		42.8	23.8
10/19/96 2:29	29.5	19.4	37.2	0									
10/19/96 2:59	29.4	19.4	37.4	0	18.9	38.3	39.5	43.6	25	36.4		43	23.5
10/19/96 3:29	29.4	19.4	37.6	0									
10/19/96 3:59	28.8	19.4	37.6	0	18.9	38.7	40.1	44	24.5	37.1		43.4	23.2
10/19/96 4:29	28.8	19.3	37.3	0									
10/19/96 4:59	28.4	19.3	37	0	18.8	39	40.7	44.4	24	37.8		43.9	23.5
10/19/96 5:29	28.4	19.1	36.7	0									
10/19/96 5:59	28.6	19	36.6	0.1	18.7	39.4	41.2	44.7	23.6	38.5		44.4	23.4
10/19/96 6:29	28.5	18.8	36	0.1									
10/19/96 6:59	28.7	18.8	35.8	0.05	18.5	39.7	41.8	45.2	23.7	39.1		44.9	23.6
10/19/96 7:29	28.7	18.7	35.4	0.11									
10/19/96 7:59	28.9	18.7	35.4	0.11	18.4	39.9	42.3	45.5	23.6	39.7		45.4	23.7
10/19/96 8:29	28.7	18.6	35	0.1									
10/19/96 8:59	28.9	18.6	35.4	0.1	18.3	40.2	42.8	46	23.3	40.2		45.9	23.5
10/19/96 9:29	29	18.6	34.9	0.11									
10/19/96 9:59	28.9	18.7	34.4	0.11	18.2	40.4	43.2	46.4	23	40.7		46.4	23.3
10/19/96 10:29	28.9	18.7	34.6	0.11									
10/19/96 10:59	29	18.8	34.1	0.11	18.2	40.6	43.6	46.9	22.8	41.1		46.9	23.1
10/19/96 11:29	29.1	18.8	33.2	0.11									
10/19/96 11:59	29.2	19	33.8	0.11	18.3	40.7	43.9	47.3	22.7	41.5		47.4	23.2
10/19/96 12:29	29.4	19.1	33.2	0.11									
10/19/96 12:59	29.6	19.3	34.1	0.12	18.3	40.8	44.3	47.8	22.9	41.9		47.9	23.5
10/19/96 13:29	29.7	19.3	32.8	0									

10/19/96 13:59	30	19.3	33.2	0.1	18.4	40.9	44.6	48.2	23.1	42.2	48.3	23.7
10/19/96 14:29	30	19.3	32.8	0.1								
10/19/96 14:59	30.4	19.4	33.2	0.1	18.5	40.9	44.8	48.6	23.3	42.4	48.8	23.9
10/19/96 15:29	30.8	19.4	33.8	0.1								
10/19/96 15:59	30.8	19.5	33.6	0.11	18.6	41	45.1	49	23.9	42.7	49.3	24.6
10/19/96 16:29	30.9	19.5	33.8	0.11								
10/19/96 16:59	31.1	19.5	33.2	0.11	18.6	41.1	45.3	49.5	23.9	42.9	49.8	24.5
10/19/96 17:29	31.6	19.5	33.7	0.11								
10/19/96 17:59	32	19.4	34	0	18.7	41.2	45.5	49.8	24.4	43	50.3	24.9
10/19/96 18:29	32.5	19.4	34.4	0.1								
10/19/96 18:59	32.9	19.4	34.9	0.11	18.7	41.2	45.7	50.2	25.6	43.2	50.8	25.1
10/19/96 19:29	33.1	19.5	35.2	0.07								
10/19/96 19:59	33.5	19.5	35.4	0.1	18.7	41.2	45.9	50.6	26	43.4	51.3	25.7
10/19/96 20:29	33.7	19.5	35.6	0.1								
10/19/96 20:59	34	19.5	35.8	0.1	18.7	41.2	46	50.9	26	43.5	51.7	25.9
10/19/96 21:29	33.9	19.3	36	0.11								
10/19/96 21:59	34.1	19.2	36.1	0.1	18.6	41.2	46.2	51.2	25.5	43.6	52.2	25.6
10/19/96 22:29	34.2	19.6	36.4	0								
10/19/96 22:59	34.3	19.4	36	0.1	18.7	41.2	46.3	51.5	24.5	43.7	52.6	25.3
10/19/96 23:29	34.5	19.3	36.6	0.1								
10/19/96 23:59	34.5	19.3	37.3	0.11	18.5	41.2	46.4	51.8	25.5	43.8	53	25.2
10/20/96 0:29	34.8	19.4	37.7	0.11								
10/20/96 0:59	34.7	19.4	37.8	0.1	18.4	41.2	46.5	52	25.1	43.9	53.3	25.3
10/20/96 1:29	34.7	19.5	37.8	0								
10/20/96 1:59	34.7	19.4	38.6	0.11	18.3	41.3	46.5	52.2	24.6	44	53.7	25.4
10/20/96 2:29	34.6	19.5	38	0.07								
10/20/96 2:59	34.8	19.5	38.5	0.1	18.3	41.3	46.6	52.4	24.3	44	54	25.2
10/20/96 3:29	34.8	19.5	38.3	0								
10/20/96 3:59	34.8	19.4	38.1	0.02	18.2	41.3	46.6	52.6	24.4	44.1	50.3	25.2
10/20/96 4:29	34.9	19.4	38.4	0.1								
10/20/96 4:59	35	19.3	38.3	0.02	18.2	41.2	46.7	52.7	24.3	44.1	50.4	25.1
10/20/96 5:29	35.1	19.3	38.5	0.1								
10/20/96 5:59	35	19.1	39.2	0.11	18.1	41.2	46.7	52.8	24	44.1	50.5	24.9
10/20/96 6:29	35	18.9	40.8	0.12								

10/20/96 6:59	35.5	19	41.6	0.11	18.1	41.2	46.7	52.9	24.1	44.1	50.6	54.9	25
10/20/96 7:29	35.6	19	42.2	0.11									
10/20/96 7:59	35.7	19.1	42.6	0.11	18.1	41.2	46.7	53	24.3	44.1	50.7	55.1	25.3
10/20/96 8:29	35.9	19.1	43.5	0.1									
10/20/96 8:59	36.1	19.1	44	0.11	18	41.1	46.7	53.1	24.6	44.1	50.7	55.2	25.5
10/20/96 9:29	36.5	19.1	44.8	0.1									
10/20/96 9:59	36.9	19.3	45.2	0.11	18.1	41.2	46.7	53.1	25	44.1	50.8	55.3	25.7
10/20/96 10:29	36.7	19.5	45.4	0.1									
10/20/96 10:59	37.2	19.6	46.1	0	18.2	41.2	46.8	53.1	25.2	44.2	50.8	55.4	25.8
10/20/96 11:29	37.3	19.7	46.6	0									
10/20/96 11:59	37.7	19.8	47.6	0.1	18.3	41.2	46.8	53.2	25.8	44.2	50.9	55.5	26
10/20/96 12:29	37.9	20	48.2	0									
10/20/96 12:59	37.9	20	48.9	0	18.4	41.3	46.8	53.2	26	44.2	50.9	55.5	26.2
10/20/96 13:29	38	20.1	49.1	0.05									
10/20/96 13:59	38.1	20.2	49.7	0	18.5	41.3	46.9	53.3	26.1	44.2	50.9	55.5	26.3
10/20/96 14:29	38.1	20.3	49.8	0									
10/20/96 14:59	38.1	20.3	49.8	0	18.7	41.3	46.9	53.3	25.8	44.3	51	55.6	26.1
10/20/96 15:29	38	20.4	49.5	0									
10/20/96 15:59	38.4	20.5	50	0	18.8	41.4	47	53.4	25.7	44.3	51	55.6	26
10/20/96 16:29	38	20.5	50	0									
10/20/96 16:59	38.1	20.6	50.4	0	19	41.4	47.1	53.4	25.5	44.3	51.1	55.6	26.3
10/20/96 17:29	38	20.6	49.8	0									
10/20/96 17:59	38	20.7	48.9	0	19.1	41.5	47.1	53.5	26.2	44.4	51.1	55.6	26.5
10/20/96 18:29	38.2	20.6	47.5	0									
10/20/96 18:59	38.2	20.6	46.9	0	19.1	41.6	47.2	53.5	26.2	44.4	51.1	55.7	26.5
10/20/96 19:29	38.3	20.6	43.9	0.1									
10/20/96 19:59	38.2	20.5	42.2	0.1	19.2	41.6	47.2	53.5	26.5	44.5	51.2	55.7	26.5
10/20/96 20:29	38.1	20.3	41.6	0.1									
10/20/96 20:59	38.3	20.3	40.9	0.1	19.2	41.7	47.3	53.5	26.3	44.5	51.2	55.7	26.5
10/20/96 21:29	38.1	20.3	41.5	0.05									
10/20/96 21:59	37.9	20	41.9	0.11									
10/20/96 22:58	44.4	19.4	44.6	0.12									
10/20/96 23:28	44.5	20	44.3	0.1									
10/20/96 23:58	44.7	20.3	44.5	0	19.6	41.8	47.4	53.4	25.5	44.6	51.3	55.6	26.2

10/21/96 17:28	43.3	21.1	51.1	0	20	43.1	48.1	53.1	25.8	45.5	51.7	55.1	26.2
10/21/96 17:58	43.2	21.1	50.1	0.1									
10/21/96 18:28	43.1	21.1	49.4	0									
10/21/96 18:58	43.1	21.1	50	0									
10/21/96 19:28	43.1	21.1	48.9	0									
10/21/96 19:58	43	21	49.3	0									
10/21/96 20:28	42.9	21	48.1	0									
10/21/96 20:58	42.9	21.1	47.5	0	20	43.2	48.2	53.1	25.3	45.6	51.8	55	25.6
10/21/96 21:28	42.9	21	47.5	0									
10/21/96 21:58	42.8	21	47.8	0									
10/21/96 22:28	42.7	21	48	0									
10/21/96 22:58	42.8	21	48.3	0									
10/21/96 23:28	42.8	21	49.1	0									
10/21/96 23:58	42.9	21	48.4	0.1	20	43.4	48.3	53.1	25.4	45.8	52	55	25.6
10/22/96 0:28	42.7	21	48.7	0									
10/22/96 0:58	42.8	21	49.3	0									
10/22/96 1:28	42.8	21	48.4	0									
10/22/96 1:58	42.7	21	48.8	0									
10/22/96 2:28	42.7	21	48.2	0									
10/22/96 2:58	42.7	21	47.9	0	19.9	43.5	48.4	53	25.4	45.9	52.1	55	25.5
10/22/96 3:28	42.8	21	48.6	0									
10/22/96 3:58	42.9	21	48.5	0									
10/22/96 4:28	42.9	21	48.6	0									
10/22/96 4:58	42.9	20.8	48.5	0									
10/22/96 5:28	42.8	21	48.2	0									
10/22/96 5:58	42.8	21	48.4	0	20	43.6	48.4	53	25.5	45.9	52.2	55	25.8
10/22/96 6:28	42.7	21	48.4	0									
10/22/96 6:58	42.7	21	48.2	0									
10/22/96 7:28	42.7	21	48.1	0									
10/22/96 7:58	42.7	21	48.2	0									
10/22/96 8:28	42.8	21	48.5	0									
10/22/96 8:58	42.7	21	47.9	0	20	43.7	48.5	53	25.5	46	52.4	55	25.8
10/22/96 9:28	42.7	21	48.3	0									
10/22/96 9:58	42.7	21	48.7	0									

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10/23/96 3:28	42.5	20.7	59.5	0	19.5	43.7	48.8	53.7	23.6	46.1	53.4	55.7	24
10/23/96 3:58	42.4	19.8	63.4	0									
10/23/96 4:28	42.5	20.1	63.1	0.1									
10/23/96 4:58	42.5	20.2	63.3	0									
10/23/96 5:28	42.6	20	64.1	0									
10/23/96 5:58	42.7	19.5	65	0.11	19.5	43.7	48.8	53.7	23.6	46.1	53.4	55.7	24
10/23/96 6:28	42.5	19.5	61.3	0.11									
10/23/96 6:58	42.4	19.1	57.9	0.11									
10/23/96 7:28	42.2	19.4	57.4	0.11									
10/23/96 7:58	42.2	19.1	54.7	0.05									
10/23/96 8:28	42.3	18.7	52.5	0.12									
10/23/96 8:58	42.5	16.7	50.7	0	18.9	43.5	48.7	53.7	22.3	46	53.4	55.8	22.9
10/23/96 9:28	42.5	15.2	48.2	0.13									
10/23/96 9:58	42.2	16.5	44	0.13									
10/23/96 10:28	42.3	16.7	44.4	0.13									
10/23/96 10:58	42.4	16.7	45.9	0.13									
10/23/96 11:28	42.3	16.8	46.5	0.13									
10/23/96 11:58	42.2	17.2	46.3	0.13	17.2	42.9	48.3	53.6	19.6	45.6	53.3	55.9	20.3
10/23/96 12:28	42.1	17.2	46.3	0.12									
10/23/96 12:58	42.4	17.6	45.3	0.13									
10/23/96 13:28	42.7	18.3	44.2	0.12									
10/23/96 13:58	42.9	18.5	44	0.11									
10/23/96 14:28	43	18.1	45.3	0.11									
10/23/96 14:58	43.3	17.9	45.6	0.12	17.9	42.6	47.9	53.4	22	45.3	53.2	55.8	22.5
10/23/96 15:28	43.2	17.6	46	0									
10/23/96 15:58	43.3	17.5	47.7	0.12									
10/23/96 16:28	43.5	17.7	47.6	0.13									
10/23/96 16:58	43.4	17.6	47.1	0.12									
10/23/96 17:28	43.3	17.6	47.8	0.13									
10/23/96 17:58	43.2	17.4	47.3	0.12	17.8	42.1	47.6	53.3	22	44.9	53	55.8	22.4
10/23/96 18:28	43.1	17.1	46.8	0.13									
10/23/96 18:58	42.9	17.3	45.1	0.14									
10/23/96 19:28	43.1	17.6	45.1	0.13									
10/23/96 19:58	43.3	17.5	45.6	0.12									

10/23/96 20:28	43.1	17	45.5	0.13	17.5	41.6	47.2	53.2	21.1	44.5	52.8	55.7	21.6
10/23/96 20:58	43	17	45.5	0.12									
10/23/96 21:28	42.9	16.8	45.7	0.14									
10/23/96 21:58	42.9	16.7	45.9	0.14									
10/23/96 22:28	42.9	16.6	46.1	0.14									
10/23/96 22:58	42.7	16.5	46	0.13									
10/23/96 23:28	42.7	16.3	45.6	0.13									
10/23/96 23:58	42.6	16.3	45.3	0.13	17	41	46.8	53.1	20.2	44	52.4	55.7	20.8
10/24/96 0:28	42.8	16	44.8	0.11									
10/24/96 0:58	42.8	15.6	45	0.15									
10/24/96 1:28	42.8	15.2	45.4	0.15									
10/24/96 1:58	42.9	14.9	46.6	0.15									
10/24/96 2:28	43	14.7	48.4	0.16									
10/24/96 2:58	43.1	14.7	50	0.15	15.9	40.5	46.3	52.9	18.3	43.4	52	55.5	19.3
10/24/96 3:28	43.1	14.6	51.8	0.15									
10/24/96 3:58	43.1	14.6	52.8	0.16									
10/24/96 4:28	43.1	14.7	53.4	0.14									
10/24/96 4:58	43.3	14.8	54.1	0.14									
10/24/96 5:28	43.1	15.1	54.3	0.14									
10/24/96 5:58	43.1	15.3	54.6	0.14	15.3	39.8	45.6	52.5	17.9	42.7	52.5	55.2	18.8
10/24/96 6:28	43.1	15.2	56.1	0.13									
10/24/96 6:58	43	15.1	57.8	0.12									
10/24/96 7:28	42.8	15.3	58.4	0.12									
10/24/96 7:58	42.9	15.6	58.1	0.13									
10/24/96 8:28	42.9	16	58	0.12									
10/24/96 8:58	43	16.2	58	0.12	15.6	39.2	45.1	52.2	18.5	42.1	50.9	54.9	19.3
10/24/96 9:28	42.8	16.2	58	0.14									
10/24/96 9:58	42.8	16.1	58.1	0.12									
10/24/96 10:28	42.8	15.9	58.8	0.11									
10/24/96 10:58	42.8	15.7	59.6	0.11									
10/24/96 11:28	42.9	15.7	58.4	0.13									
10/24/96 11:58	43	16.1	56.5	0.12	15.9	38.7	44.6	52.1	18.9	41.5	50.4	54.6	19.6
10/24/96 12:28	43.2	16.3	56.2	0.05									
10/24/96 12:58	43.2	16	56.2	0.13									

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10/25/96 23:28	42.5	18.7	46	0.1	17.8	36.7	42.9	52	21.9	38.6	47.6	53.5	22
10/25/96 23:58	42.5	18.7	46.2	0	17.8	36.7	42.9	52	21.9	38.6	47.6	53.5	22
10/26/96 0:28	42.5	18.7	46.2	0.1									
10/26/96 0:58	42.5	18.6	45.4	0.1									
10/26/96 1:28	42.5	18.5	45.7	0.1									
10/26/96 1:58	42.5	18.5	45.8	0.1									
10/26/96 2:28	42.5	18.5	45.8	0.1									
10/26/96 2:58	42.6	18.3	45.7	0.1	17.7	36.8	42.9	52.1	21.5	38.6	47.6	53.6	21.6
10/26/96 3:28	42.6	18.3	46.3	0.11									
10/26/96 3:58	42.6	18.3	46.2	0.1									
10/26/96 4:28	42.7	18.1	46.6	0.11									
10/26/96 4:58	42.8	18	47	0.1									
10/26/96 5:28	42.8	18	47.3	0.11									
10/26/96 5:58	42.9	18.2	47.9	0.1	17.5	36.8	42.8	52.1	21	38.6	47.6	53.7	21.1
10/26/96 6:28	42.8	18.3	48.3	0									
10/26/96 6:58	43	18.4	48.9	0									
10/26/96 7:28	43	18.5	49.7	0									
10/26/96 7:58	43	18.5	50.3	0									
10/26/96 8:28	43	18.5	50.6	0									
10/26/96 8:58	43.1	18.6	51.2	0	17.5	36.8	42.8	52.2	21.5	38.6	47.6	53.7	21.5
10/26/96 9:28	43.1	18.6	52	0									
10/26/96 9:58	43.1	18.7	52.4	0									
10/26/96 10:28	43.1	18.7	52.7	0									
10/26/96 10:58	43.1	18.8	53.4	0									
10/26/96 11:28	43.1	18.8	54	0									
10/26/96 11:58	43.2	18.8	54.4	0	17.7	36.9	42.8	52.3	21.9	38.6	47.6	53.8	21.9
10/26/96 12:28	43.2	19	55	0									
10/26/96 12:58	43.2	19	55.2	0									
10/26/96 13:28	43.2	19.1	55.6	0									
10/26/96 13:58	43.3	19.1	55.9	0									
10/26/96 14:28	43.3	19.2	56.5	0									
10/26/96 14:58	43.3	19.3	57	0	18	36.9	42.9	52.5	22.5	38.7	47.6	53.9	22.6
10/26/96 15:28	43.3	19.4	57	0									
10/26/96 15:58	43.3	19.4	57.2	0									

10/26/96 16:28	43.4	19.5	57.8	0	0	18.4	37.1	43	52.7	22.9	38.8	47.7	54	22.9
10/26/96 16:58	43.3	19.5	58.1	0	0									
10/26/96 17:28	43.4	19.6	58.6	0	0									
10/26/96 17:58	43.3	19.6	58.9	0	0									
10/26/96 18:28	43.4	19.6	59	0	0									
10/26/96 18:58	43.3	19.6	58.7	0	0									
10/26/96 19:28	43.3	19.6	58.4	0	0									
10/26/96 19:58	43.4	19.7	58.7	0	0									
10/26/96 20:28	43.4	19.7	58.8	0	0									
10/26/96 20:58	43.4	19.7	59.5	0	0	18.6	37.3	43.1	52.9	23	38.9	47.8	54.2	23.1
10/26/96 21:28	43.4	19.7	59.6	0	0									
10/26/96 21:58	43.5	19.6	59.5	0	0									
10/26/96 22:28	43.7	19.7	59.2	0	0									
10/26/96 22:58	43.7	19.6	58.8	0	0									
10/26/96 23:28	43.6	19.6	59.1	0	0									
10/26/96 23:58	43.5	19.6	59.7	0	0	18.6	37.4	43.2	53.1	22.8	39	47.9	54.3	22.9
10/27/96 0:28	43.5	19.6	61	0	0									
10/27/96 0:58	43.5	19.6	61.5	0	0									
10/27/96 1:28	43.5	19.6	61.7	0	0									
10/27/96 1:58	43.6	19.7	61.9	0	0									
10/27/96 2:28	43.6	19.7	62.4	0	0									
10/27/96 2:58	43.7	19.7	62.8	0	0	18.6	37.5	43.3	53.2	22.7	39.1	47.9	54.5	22.8
10/27/96 3:28	43.7	19.8	63.2	0	0									
10/27/96 3:58	43.7	19.8	63.3	0	0									
10/27/96 4:28	43.7	19.8	63.7	0	0									
10/27/96 4:58	43.7	20	64.2	0	0									
10/27/96 5:28	43.8	20	64.5	0	0									
10/27/96 5:58	43.8	20	65	0	0	18.8	37.7	43.4	53.4	23	39.2	48	54.6	23.1
10/27/96 6:28	43.8	20	65.5	0	0									
10/27/96 6:58	43.8	20.1	65.7	0	0									
10/27/96 7:28	43.8	20.1	65.9	0	0									
10/27/96 7:58	43.8	20.2	66.1	0	0									
10/27/96 8:28	43.9	20.2	66.4	0	0									
10/27/96 8:58	43.8	20.2	66.6	0	0	19	37.8	43.5	53.5	23.2	39.4	48.1	54.7	23.4

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10/28/96 2:28	44.3	18.6	45.9	0.1	18.9	38.3	44	53.9	21	40.1	48.6	55.4	21.3
10/28/96 2:58	44.8	17.7	47.7	0	0								
10/28/96 3:28	45.1	18.5	46.1	0									
10/28/96 3:58	45.1	18.7	46.1	0									
10/28/96 4:28	45.2	18.7	46.1	0.07									
10/28/96 4:58	45.4	18.5	45.9	0									
10/28/96 5:28	45.4	18	43.5	0									
10/28/96 5:58	45.4	18	42.9	0	18.4	38.2	43.8	53.7	20.5	40	48.5	55.2	20.8
10/28/96 6:28	45.5	18	43.2	0									
10/28/96 6:58	45.5	18	43	0									
10/28/96 7:28	45.5	17.7	42.9	0									
10/28/96 7:58	45.5	17.6	42.6	0.05									
10/28/96 8:28	45.5	17.6	42.7	0									
10/28/96 8:58	45.6	17.5	42.3	0	17.8	37.9	43.5	53.4	19.8	39.8	48.4	55	20.2
10/28/96 9:28	45.6	17.5	41.8	0									
10/28/96 9:58	45.6	17.5	41.4	0									
10/28/96 10:28	45.3	17.9	41.6	0									
10/28/96 10:58	45.5	16.6	43	0.12									
10/28/96 11:28	45.5	16.4	41.8	0									
10/28/96 11:58	45.1	17.1	40.7	0	17.5	37.6	43.2	53.2	19.7	39.5	48.1	54.8	19.9
10/28/96 12:28	45.2	17.7	39.4	0.11									
10/28/96 12:58	45.3	18.2	39	0									
10/28/96 13:28	45.1	18.5	37.6	0									
10/28/96 13:58	45.2	18.6	38.2	0									
10/28/96 14:28	45.1	18.6	38.7	0									
10/28/96 14:58	44.9	19.3	35.7	0	17.8	37.3	42.9	53	20.7	39.2	47.8	54.5	21
10/28/96 15:28	44.9	19.2	35.6	0									
10/28/96 15:58	44.8	19.1	36.2	0									
10/28/96 16:28	44.7	19.2	36.5	0									
10/28/96 16:58	44.6	19.3	35.6	0									
10/28/96 17:28	44.8	17.6	38.6	0									
10/28/96 17:58	44.7	17.2	37.9	0	18.1	37	42.7	52.9	21.1	38.9	47.6	54.3	21.2
10/28/96 18:28	44.5	18.4	37.6	0									
10/28/96 18:58	44.6	18.5	38	0									

10/29/96 12:28	42.6	15.5	40	0.1	15.7	34.4	40.3	51.1	18	36.2	45.1	52.1	18
10/29/96 12:58	42.5	15.7	39.5	0									
10/29/96 13:28	42.4	16.3	39.1	0									
10/29/96 13:58	42.2	16.1	39.2	0									
10/29/96 14:28	42.1	16.2	41.3	0									
10/29/96 14:58	42.2	16.4	41.3	0	15.7	34.4	40.3	51.1	18	36.2	45.1	52.1	18
10/29/96 15:28	42.2	15.7	52.5	0.07									
10/29/96 15:58	41.8	16.5	52	0									
10/29/96 16:28	42	16.8	52.8	0									
10/29/96 16:58	41.9	17.2	52.8	0									
10/29/96 17:28	41.8	17.4	52.8	0									
10/29/96 17:58	41.8	17.5	52.8	0	16.2	34.1	39.9	50.8	20.1	35.7	44.6	51.7	20
10/29/96 18:28	41.9	17.5	54.2	0									
10/29/96 18:58	41.7	17.3	54.5	0									
10/29/96 19:28	41.6	17.3	54.9	0									
10/29/96 19:58	41.5	17.3	56.8	0									
10/29/96 20:28	41.3	17.2	57	0									
10/29/96 20:58	41.2	17.2	57.7	0	16.5	33.8	39.7	50.6	20.2	35.3	44.2	51.3	20.1
10/29/96 21:28	41.1	17.1	58	0									
10/29/96 21:58	40.9	17.1	58.4	0									
10/29/96 22:28	40.7	17.1	59.9	0									
10/29/96 22:58	40.7	17.1	61.4	0									
10/29/96 23:28	40.6	16.6	65.5	0									
10/29/96 23:58	40.6	17	65.5	0	16.3	33.6	39.5	50.3	19.3	35	43.9	50.9	19.1
10/30/96 0:28	40.4	17	67.3	0									
10/30/96 0:58	40.3	17.2	66.4	0									
10/30/96 1:28	40.2	17.1	66.9	0									
10/30/96 1:58	40.1	17	64.6	0									
10/30/96 2:28	40	16.7	62.6	0.05									
10/30/96 2:58	39.9	16.5	61.9	0.05	16.1	33.3	39.3	50.1	18.8	34.7	43.5	50.6	18.8
10/30/96 3:28	39.6	16.4	61.8	0									
10/30/96 3:58	39.5	16.3	62	0									
10/30/96 4:28	39.4	16.2	61.6	0									
10/30/96 4:58	39.2	16.2	61	0									

10/30/96 5:28	39.2	16.3	59.6	0	15.8	33.1	39	49.8	17.6	34.4	43.1	50.2	17.5
10/30/96 5:58	39.1	16.3	59.5	0									
10/30/96 6:28	39	16.3	61.8	0									
10/30/96 6:58	38.8	16.2	62.6	0									
10/30/96 7:28	38.9	16	65.7	0									
10/30/96 7:58	39.1	15.6	62.8	0									
10/30/96 8:28	39	15	61.3	0									
10/30/96 8:58	38.8	14.7	60.5	0	15.5	32.8	38.7	48.5	17	34.1	42.8	49.8	17
10/30/96 9:28	38.6	14.5	62	0									
10/30/96 9:58	38.6	14.2	65	0.05									
10/30/96 10:28	38.5	14.1	63.4	0.07									
10/30/96 10:58	38.4	14.2	60.5	0									
10/30/96 11:28	38.3	14.1	59.5	0									
10/30/96 11:58	38.1	14	56.7	0	14.6	32.5	38.3	49.1	15.6	33.8	42.4	49.4	15.7
10/30/96 12:28	37.9	13.9	54.4	0									
10/30/96 12:58	37.8	14.8	53.7	0									
10/30/96 13:28	37.7	14.5	54.6	0									
10/30/96 13:58	37.7	14	53.6	0									
10/30/96 14:28	37.6	14.1	53.1	0									
10/30/96 14:58	37.4	14.1	51.9	0	14.4	32.1	37.9	48.6	15.6	33.4	42	48.9	15.7
10/30/96 15:28	37.2	13.6	50.6	0									
10/30/96 15:58	37.1	13.3	52.3	0									
10/30/96 16:28	37	13.2	51.2	0.02									
10/30/96 16:58	36.9	13	51	0									
10/30/96 17:28	36.7	13	48.7	0									
10/30/96 17:58	36.5	13.1	48.3	0	13.7	31.6	37.4	48.1	14.5	33	41.5	48.4	14.6
10/30/96 18:28	36.5	13	46.1	0									
10/30/96 18:58	36.2	12.6	43.8	0									
10/30/96 19:28	35.9	12.3	42.8	0									
10/30/96 19:58	35.8	12.2	41.5	0.13									
10/30/96 20:28	35.7	12.4	41	0									
10/30/96 20:58	35.6	12.5	40.3	0	13.1	31	36.9	47.6	13.8	32.4	41	47.8	13.9
10/30/96 21:28	35.3	12.3	39.4	0									
10/30/96 21:58	35.3	12.5	38.8	0.02									

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11/3/96 2:00	24.8	13.9	30.2	0	13.2	25.4	19.6	34.2	17.7	26.5	31.7	33.6	17.2
11/3/96 3:00	24.9	14.7	30.8	0	0	0	0	0	0	0	0	0	0
11/3/96 4:00	25	15	31.8	0	0	0	0	0	0	0	0	0	0
11/3/96 5:00	25	15	31.6	0	0	0	0	0	0	0	0	0	0
11/3/96 6:00	25.1	15	31.9	0	0	0	0	0	0	0	0	0	0
11/3/96 7:00	25.2	14.8	32.2	0	0	0	0	0	0	0	0	0	0
11/3/96 8:00	25.2	14.8	32.9	0	0	0	0	0	0	0	0	0	0
11/3/96 9:00	25.2	15.2	34.4	0	0	0	0	0	0	0	0	0	0
11/3/96 10:00	25.3	15	32.8	0	0	0	0	0	0	0	0	0	0
11/3/96 11:00	25.1	14.6	33.1	0	0	0	0	0	0	0	0	0	0
11/3/96 12:00	25	15	32.1	0	0	0	0	0	0	0	0	0	0
11/3/96 13:00	24.9	15.3	32.9	0	0	0	0	0	0	0	0	0	0
11/3/96 14:00	24.8	15.5	34.1	0	0	0	0	0	0	0	0	0	0
11/3/96 15:00	24.9	15.7	34.3	0	13.5	25.2	28.7	33.9	17.8	25.5	30.4	33.1	17.6
11/3/96 16:00	25	15.8	34.4	0	0	0	0	0	0	0	0	0	0
11/3/96 17:00	25	15.8	31.2	0	0	0	0	0	0	0	0	0	0
11/3/96 18:00	25.2	15.6	30.8	0	0	0	0	0	0	0	0	0	0
11/3/96 19:00	25.2	15.3	30.4	0	0	0	0	0	0	0	0	0	0
11/3/96 20:00	25.2	14.7	30.6	0	0	0	0	0	0	0	0	0	0
11/3/96 21:00	25	14.3	30.4	0	0	0	0	0	0	0	0	0	0
11/3/96 22:00	24.8	14.1	29.4	0	0	0	0	0	0	0	0	0	0
11/3/96 23:00	24.7	13.9	29.2	0	0	0	0	0	0	0	0	0	0
11/4/96 0:00	24.4	13.4	29	0	0	0	0	0	0	0	0	0	0
11/4/96 1:00	24.1	13.3	29	0	0	0	0	0	0	0	0	0	0
11/4/96 2:00	24.1	13.1	29	0	0	0	0	0	0	0	0	0	0
11/4/96 3:00	23.9	13.1	28.8	0	13.2	25.1	28.1	33.3	17.1	24.8	30.1	32.7	16.5
11/4/96 4:00	23.8	12.8	29	0	0	0	0	0	0	0	0	0	0
11/4/96 5:00	23.6	12.9	29.2	0	0	0	0	0	0	0	0	0	0
11/4/96 6:00	23.7	13.2	29	0	0	0	0	0	0	0	0	0	0
11/4/96 7:00	23.7	13.1	29.6	0	0	0	0	0	0	0	0	0	0
11/4/96 8:00	23.7	13.1	30.7	0	0	0	0	0	0	0	0	0	0
11/4/96 9:00	23.7	13.8	31.1	0	0	0	0	0	0	0	0	0	0
11/4/96 10:00	23.9	14.3	31.1	0	0	0	0	0	0	0	0	0	0
11/4/96 11:00	24.2	14.9	32.8	0	0	0	0	0	0	0	0	0	0

11/4/96 12:00	24.4	15.3	34	0	0	13.4	24.5	27.6	33	16.1	24.7	29.1	32.2	15.9
11/4/96 13:00	24.8	15.4	33.5	0										
11/4/96 14:00	24.8	15.8	36	0										
11/4/96 15:00	25.4	13.6	38.2	0.1	13.4	24.5	27.6	33	16.1	24.7	29.1	32.2	15.9	
11/4/96 16:00	24.7	13	36.6	0										
11/4/96 17:00	24.2	15.1	37.5	0										
11/4/96 18:00	24.3	15.2	36.4	0										
11/4/96 19:00	24	14.9	38.9	0										
11/4/96 20:00	23.8	15.1	37.8	0										
11/4/96 21:00	23.7	15.2	41.3	0										
11/4/96 22:00	23.6	15.2	37.4	0										
11/4/96 23:00	23.5	15.2	39.8	0										
11/5/96 0:00	23.5	15.2	37.9	0										
11/5/96 1:00	23.4	15.1	36.7	0										
11/5/96 2:00	23.3	15.1	37.8	0										
11/5/96 3:00	23.2	14.8	36.5	0										
11/5/96 4:00	23.3	14.8	37.1	0										
11/5/96 5:00	23.1	14.5	39.3	0										
11/5/96 6:00	23.1	15.1	39.9	0										
11/5/96 7:00	23.2	15.1	41.2	0										
11/5/96 8:00	23.1	15.1	43	0										
11/5/96 9:00	23.1	15.1	44.3	0										
11/5/96 10:00	23.2	15.1	46.1	0										
11/5/96 11:00	23.5	16	47	0										
11/5/96 12:00	24	16.2	45.4	0										
11/5/96 13:00	24.3	16.4	45.9	0										
11/5/96 14:00	24.7	16.7	44.6	0										
11/5/96 15:00	24.8	17	44.3	0	13.9	23.8	26.6	31.8	16.2	23.9	28	31	16	
11/5/96 16:00	24.8	15.8	45.7	0										
11/5/96 17:00	24.7	16.2	45.5	0										
11/5/96 18:00	24.5	16.3	46.7	0										
11/5/96 19:00	24.3	16.2	47.7	0										
11/5/96 20:00	24.2	16.2	48.5	0										
11/5/96 21:00	24.1	16.3	49.2	0										

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11/5/96 22:00	24.1	16.3	49.2	0	15.1	24.1	26.7	31.5	17.8	24	17.7	30.8	17.6
11/5/96 23:00	24.1	16.2	49.2	0									
11/6/96 0:00	24	16.3	50.2	0									
11/6/96 1:00	24	16.3	50.6	0									
11/6/96 2:00	24.1	16.1	52	0									
11/6/96 3:00	24.1	16.2	52.1	0									
11/6/96 4:00	24.1	16.1	52.9	0									
11/6/96 5:00	24.2	16.2	52.9	0									
11/6/96 6:00	24.1	16.1	53.5	0									
11/6/96 7:00	24.2	16	56.3	0									
11/6/96 8:00	24.2	16.1	56.5	0									
11/6/96 9:00	24.2	16.4	55.7	0									
11/6/96 10:00	24.3	16.6	57.2	0									
11/6/96 11:00	24.6	17.2	59.8	0									
11/6/96 12:00	25.1	17.7	62.4	0									
11/6/96 13:00	25.6	18.1	62.9	0									
11/6/96 14:00	25.7	18.3	66.1	0									
11/6/96 15:00	25.7	18.5	65.5	0	15.1	24.1	26.7	31.5	17.8	24	17.7	30.8	17.6
11/6/96 16:00	25.8	17.8	68.4	0									
11/6/96 17:00	25.8	18.3	66.3	0									
11/6/96 18:00	26.1	18.5	66.8	0									
11/6/96 19:00	26.3	18.6	66.2	0									
11/6/96 20:00	26.6	18.7	66	0									
11/6/96 21:00	26.7	18.8	66	0									
11/6/96 22:00	26.9	18.8	66.2	0									
11/6/96 23:00	27	19	66.3	0									
11/7/96 0:00	27.2	19.1	67.1	0									
11/7/96 1:00	27.4	19.2	67.2	0									
11/7/96 2:00	27.5	19.3	67.4	0									
11/7/96 3:00	27.7	19.4	67.3	0									
11/7/96 4:00	27.7	19.5	67.1	0									
11/7/96 5:00	28	19.7	66.5	0									
11/7/96 6:00	28.1	19.8	66.1	0									
11/7/96 7:00	28.2	19.9	65.8	0									

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11/7/96 8:00	28.1	19.7	63.2	0	18.2	28	32.6	27.6	22.6	25.3	28.8	32.2	22.5						
11/7/96 9:00	27.7	19.5	59.5	0															
11/7/96 10:00	27.6	19.3	55.6	0															
11/7/96 11:00	27.5	19.4	55	0															
11/7/96 12:00	27.6	18.6	51	0															
11/7/96 13:00	27.4	18.7	49.4	0															
11/7/96 14:00	27.4	18.2	47.8	0															
11/7/96 15:00	27.5	18	46.2	0	18.2	28	32.6	27.6	22.6	25.3	28.8	32.2	22.5						
11/7/96 16:00	27.9	18.2	47.2	0															
11/7/96 17:00	27.9	18.5	48.9	0															
11/7/96 18:00	28.1	18.6	49.2	0															
11/7/96 19:00	28.4	18.7	47.8	0															
11/7/96 20:00	28.6	18.6	49	0															
11/7/96 21:00	28.9	18.6	49.8	0															
11/7/96 22:00	29.1	18.6	49.8	0															
11/7/96 23:00	29.2	18.6	50.6	0															
11/8/96 0:00	29.5	18.7	50.5	0															
11/8/96 1:00	29.6	18.7	50.1	0															
11/8/96 2:00	29.8	18.7	50.4	0															
11/8/96 3:00	30	18.7	50.2	0															
11/8/96 4:00	30.2	18.8	50	0															
11/8/96 5:00	30.3	18.7	49.4	0															
11/8/96 6:00	30.5	18.7	48.5	0															
11/8/96 7:00	30.6	18.7	48.2	0															
11/8/96 8:00	30.8	18.6	46.8	0															
11/8/96 9:00	30.8	18.6	48.4	0															
11/8/96 10:00	30.9	18.8	49.9	0															
11/8/96 11:00	31.1	18.9	50.4	0															
11/8/96 12:00	31.2	19	49.4	0															
11/8/96 13:00	31.5	19.4	50.4	0															
11/8/96 14:00	31.8	19.5	50.5	0															
11/8/96 15:00	31.9	19.6	51	0	17.5	27.7	30	36	22	27.5	31.2	36	21.8						
11/8/96 16:00	32.1	19.6	50.9	0															
11/8/96 17:00	32.3	19.6	50.4	0															

11/11/96 14:00	33.6	17	43.3	0	15.3	26.9	30.9	42.2	20.4	27.5	33.7	42.2	20.2
11/11/96 15:00	33.6	16.6	38.4	0	0	0	0	0	0	0	0	0	0
11/11/96 16:00	33.6	17	46.1	0	0	0	0	0	0	0	0	0	0
11/11/96 17:00	33.6	16.6	41.7	0	0	0	0	0	0	0	0	0	0
11/11/96 18:00	33.5	16.2	44.6	0	0	0	0	0	0	0	0	0	0
11/11/96 19:00	33.2	15.7	46.1	0	0	0	0	0	0	0	0	0	0
11/11/96 20:00	33	15.7	45.2	0	0	0	0	0	0	0	0	0	0
11/11/96 21:00	32.8	15.7	41	0	0	0	0	0	0	0	0	0	0
11/11/96 22:00	33	16.1	40.5	0	0	0	0	0	0	0	0	0	0
11/11/96 23:00	33.1	16.1	38.8	0	0	0	0	0	0	0	0	0	0
11/12/96 0:00	33	16.1	40.9	0	0	0	0	0	0	0	0	0	0
11/12/96 1:00	33	15.3	38.8	0	0	0	0	0	0	0	0	0	0
11/12/96 2:00	33.1	15.1	37.6	0	0	0	0	0	0	0	0	0	0
11/12/96 3:00	33	14.5	36.1	0	0	0	0	0	0	0	0	0	0
11/12/96 4:00	33.1	14.1	35.9	0.1	0	0	0	0	0	0	0	0	0
11/12/96 5:00	32.9	14.7	38.1	0	0	0	0	0	0	0	0	0	0
11/12/96 6:00	32.8	14.8	37.6	0.07	0	0	0	0	0	0	0	0	0
11/12/96 7:00	32.8	15	39.4	0	0	0	0	0	0	0	0	0	0
11/12/96 8:00	32.9	15	40	0	0	0	0	0	0	0	0	0	0
11/12/96 9:00	32.8	15.3	41.7	0	0	0	0	0	0	0	0	0	0
11/12/96 10:00	32.7	15.3	42.6	0	0	0	0	0	0	0	0	0	0
11/12/96 11:00	32.5	15.6	42	0	0	0	0	0	0	0	0	0	0
11/12/96 12:00	32.6	15.8	40.3	0	0	0	0	0	0	0	0	0	0
11/12/96 13:00	32.4	16	45	0	0	0	0	0	0	0	0	0	0
11/12/96 14:00	32.3	16.1	45.3	0	0	0	0	0	0	0	0	0	0
11/12/96 15:00	32.2	15.5	35.7	0	14.6	25.9	29.9	40.8	19.9	26.4	32.6	40.7	19.8
11/12/96 16:00	32	15.5	38.3	0	0	0	0	0	0	0	0	0	0
11/12/96 17:00	31.9	15.5	38.5	0	0	0	0	0	0	0	0	0	0
11/12/96 18:00	31.8	15.4	46.4	0	0	0	0	0	0	0	0	0	0
11/12/96 19:00	31.6	14.9	38.9	0.1	0	0	0	0	0	0	0	0	0
11/12/96 20:00	31.3	14.6	40.3	0	0	0	0	0	0	0	0	0	0
11/12/96 21:00	31.1	14.3	39.8	0	0	0	0	0	0	0	0	0	0
11/12/96 22:00	30.9	14.2	41.8	0	0	0	0	0	0	0	0	0	0
11/12/96 23:00	30.6	14	42	0.07	0	0	0	0	0	0	0	0	0

11/14/96 10:00	28	13.5	32.6	0	12.7	22.7	26.2	35.2	18.1	23.1	28.4	34.9	18
11/14/96 11:00	27.8	13.7	33	0									
11/14/96 12:00	27.7	13.9	33.2	0									
11/14/96 13:00	27.9	14.1	32.7	0									
11/14/96 14:00	27.8	14.2	33	0									
11/14/96 15:00	27.9	14.4	29	0	12.7	22.7	26.2	35.2	18.1	23.1	28.4	34.9	18
11/14/96 16:00	27.8	14.5	31.3	0									
11/14/96 17:00	27.5	14.1	31.6	0									
11/14/96 18:00	27.2	14.3	35.6	0									
11/14/96 19:00	27	14.3	35.7	0									
11/14/96 20:00	27	14.4	34.5	0									
11/14/96 21:00	26.9	14.3	33.8	0									
11/14/96 22:00	26.7	14.2	34	0									
11/14/96 23:00	26.6	14.1	32.5	0									
11/15/96 0:00	26.5	14	33.7	0									
11/15/96 1:00	26.3	13.9	33.8	0									
11/15/96 2:00	26.2	13.8	32.9	0									
11/15/96 3:00	26.1	13.7	32.5	0									
11/15/96 4:00	26	13.6	32.5	0									
11/15/96 5:00	25.7	13.5	32.2	0									
11/15/96 6:00	25.6	13.4	32.6	0									
11/15/96 7:00	25.5	13.5	34.4	0									
11/15/96 8:00	25.4	13.5	35	0									
11/15/96 9:00	25.2	13.6	39.5	0									
11/15/96 10:00	25.2	13.6	40.2	0									
11/15/96 11:00	25	13.5	39.1	0									
11/15/96 12:00	24.6	12.5	37.1	0									
11/15/96 13:00	24.3	12.3	34.6	0									
11/15/96 14:00	24.1	12.5	37.2	0									
11/15/96 15:00	24.1	12.5	35	0	12.2	21.6	24.7	32.1	16.8	21.8	26.4	31.7	16.7
11/15/96 16:00	24.2	12.8	32.9	0									
11/15/96 17:00	24.1	13	35.7	0									
11/15/96 18:00	24.2	13.7	38.5	0									
11/15/96 19:00	24.2	13.8	37.7	0									

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[illegible]

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11/28/96 14:00	15.3	11.6	34.5	0	10.3	18.2	19.4	19.9	13.3	18.4	20.3	19.6	13.2						
11/28/96 15:00	15.1	13.9	28.5	0															
11/28/96 16:00	15.1	11.1	33.9	0															
11/28/96 17:00	15.1	11.5	31.8	0															
11/28/96 18:00	15.1	11.4	31	0															
11/28/96 19:00	15.5	11.2	30.4	0															
11/28/96 20:00	15.7	10.6	30.2	0															
11/28/96 21:00	15.6	10.7	29.9	0															
11/28/96 22:00	15.7	10.6	29.6	0															
11/28/96 23:00	15.7	10.9	29.6	0															
11/29/96 0:00	15.7	10.9	29.6	0															
11/29/96 1:00	15.8	11	30.2	0															
11/29/96 2:00	15.8	11.3	29.6	0															
11/29/96 3:00	15.8	11.3	29.4	0															
11/29/96 4:00	15.8	10.7	28.4	0															
11/29/96 5:00	15.7	9.9	29.2	0															
11/29/96 6:00	15.6	10.3	28.8	0															
11/29/96 7:00	15.5	10.9	28.9	0															
11/29/96 8:00	15.5	10.8	28.8	0															
11/29/96 9:00	15.5	10.9	29.7	0															
11/29/96 10:00	15.5	11	30.1	0															
11/29/96 11:00	15.5	11	31.6	0															
11/29/96 12:00	15.5	11.5	33.1	0															
11/29/96 13:00	15.4	11.7	34.7	0															
11/29/96 14:00	15.1	11.2	35.9	0															
11/29/96 15:00	14.8	11.3	35.9	0	10.3	17	18.1	18.5	13.7	17	18.8	18.2	13.6						
11/29/96 16:00	14.9	11.8	35.3	0															
11/29/96 17:00	15.1	12	35.6	0															
11/29/96 18:00	15.3	12.3	35.7	0															
11/29/96 19:00	15.4	12.4	36.2	0															
11/29/96 20:00	15.6	12.5	36.7	0															
11/29/96 21:00	15.6	12.5	37.1	0															
11/29/96 22:00	15.6	12.5	37.7	0															
11/29/96 23:00	15.6	12.6	38	0															

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11/30/96 0:00	15.7	12.6	39.1	0	11.2	16.2	17.2	17.5	14.5	16	17.6	17.1	14.5
11/30/96 1:00	15.6	12.6	41.7	0									
11/30/96 2:00	15.6	12.6	42.9	0									
11/30/96 3:00	15.6	12.6	44.3	0									
11/30/96 4:00	15.6	12.6	45	0									
11/30/96 5:00	15.6	12.6	45.9	0									
11/30/96 6:00	15.5	12.7	46.6	0									
11/30/96 7:00	15.5	12.7	47.1	0									
11/30/96 8:00	15.6	12.8	48.1	0									
11/30/96 9:00	15.7	13	48.5	0									
11/30/96 10:00	15.8	13.1	50	0									
11/30/96 11:00	15.6	12.8	53.4	0									
11/30/96 12:00	15.4	12.8	55.9	0									
11/30/96 13:00	15.3	13	57.8	0									
11/30/96 14:00	15.3	13.3	58.2	0									
11/30/96 15:00	15.4	13.5	59.8	0	11.2	16.2	17.2	17.5	14.5	16	17.6	17.1	14.5
11/30/96 16:00	15.6	13.6	60.8	0									
11/30/96 17:00	15.6	13.7	61.2	0									
11/30/96 18:00	15.8	13.8	61.8	0									
11/30/96 19:00	15.8	14	61.3	0									
11/30/96 20:00	16.1	14.1	60.8	0									
11/30/96 21:00	16.2	14.2	59.9	0									
11/30/96 22:00	16.2	14.3	59.2	0									
11/30/96 23:00	16.3	14.5	58.5	0									
12/1/96 0:00	16.5	14.6	57.8	0									
12/1/96 1:00	16.6	14.6	57.3	0									
12/1/96 2:00	16.6	14.7	56.8	0									
12/1/96 3:00	16.7	14.8	56.6	0									
12/1/96 4:00	16.7	14.8	56.4	0									
12/1/96 5:00	16.8	14.9	56.2	0									
12/1/96 6:00	16.9	15	56.2	0									
12/1/96 7:00	16.9	15.1	56.7	0									
12/1/96 8:00	17	15.3	57.1	0									
12/1/96 9:00	17.1	15.2	61.1	0									

Michigan State University - Compost Aeration Experiment: Trial #3, moisture contents

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Date: 9/30/96

Description: Initial moisture content of raw material mixture

Sample	Wet Wt + Tin Wt (g)	Dry Wt. + Tin Wt (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 16 in	278.52	221.7	146.1	42.91
16 in - 32 in	268.56	220.8	148.5	39.78
32 in - 48 in	303.39	234.5	148.3	44.42

Date: 10/16/96

Description: Moisture content of compost sampled during turning

Sample	Wet Wt + Tin Wt (g)	Dry Wt. + Tin Wt (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 16 in	341.6	271.9	145.9	35.62
16 in - 24 in	298.9	249.8	148.3	32.60
24 in - 36 in	315.8	246.5	148	41.30
36 in - 41.5 in	512.6	450.7	361.8	41.05

Date: 10/16/96

Description: Moisture content of mixed compost with water added

Sample	Wet Wt + Tin Wt (g)	Dry Wt. + Tin Wt (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 12 in	456.2	262.6	145.9	62.39
12 in - 24 in	396.7	224.6	148.3	69.28
24 in - 40 in	454.6	240	148	69.99

Date: 12/5/96

Description: Moisture content of compost sampled during turning

Sample	Wet Wt + T (g)	Dry Wt. + T (g)	Tin Wt (g)	Moisture Content Wet Basis, %
0 in - 12 in	456.7	255	148.3	65.40
12 in - 24 in	472.1	255.6	145.9	66.37
24 in - 31 in	441.8	289.5	148	51.84

Michigan State University - Compost Aeration Experiment: Trial #4

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Time	Ht in	Solomat datalogger				CR21X datalogger															
		deg C		m/s		Thermocouple Temperature Readings, deg C												Oxygen content, percent			
		Top	Inlet	Inlet	REF	1	2	3	4	5	6	7	8	Plen	Inlet	1 ft	2 ft	Air			
2/25/97 22:00		13.3	13.2	0	12.6	12.1	12.4	12.7	13.2	12.1	12.4	12.7	14								
2/25/97 23:00		13.3	13.2	0	12.8	12.2	12.5	13.1	13.8	12.2	12.5	13	14.5								
2/26/97 0:00	48	13.3	13.1	0	12.5	12.9	13.3	12.7	13	12.9	12.6	12.2	14.1	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
2/26/97 1:00		13.2	13.1	0																	
2/26/97 2:00		13.1	13	0																	
2/26/97 3:00		13	12.9	0	11.8	13.5	13.4	13	13.8	13.2	13.4	13	14.3								
2/26/97 4:00		12.9	12.9	0																	
2/26/97 5:00		12.9	12.8	0																	
2/26/97 6:00		12.9	12.7	0	11.7	13.8	13.9	13.4	14.1	13.6	13.8	13.4	14.4								
2/26/97 7:00		12.8	12.7	0																	
2/26/97 8:00		12.8	12.7	0																	
2/26/97 9:00		12.7	12.7	0	11.7	14.1	14.2	13.8	14.3	14	14.2	13.9	14.6								
2/26/97 10:00		12.7	12.6	0																	
2/26/97 11:00		12.6	12.5	0																	
2/26/97 12:00		12.4	12.4	0	11.2	14.4	14.6	14.2	14.6	14.3	14.6	14.2	15								
2/26/97 13:00		12.3	12.3	0																	
2/26/97 14:00		12.3	12.3	0																	
2/26/97 15:00		12.4	12.3	0	11.4	14.6	14.9	14.5	14.8	14.6	14.9	14.6	15.4								
2/26/97 16:00		12.5	12.4	0																	
2/26/97 17:00		12.6	12.4	0																	
2/26/97 18:00		12.5	12.5	0	11.7	14.9	15.2	14.9	15	14.9	15.2	15	15.9								
2/26/97 19:00		12.4	12.5	0																	
2/26/97 20:00		12.5	12.5	0																	
2/26/97 21:00		12.4	12.5	0	11.5	15.1	15.5	15.2	15.4	15.2	15.6	15.4	16.1								
2/26/97 22:00		12.6	12.6	0																	
2/26/97 23:00		12.8	12.8	0																	
2/27/97 0:00	46	12.9	12.9	0	12.2	15.3	15.2	15.6	15.7	15.4	15.9	15.8	16.5	13	12.9	14.8	16.8	19.8			

2/27/97 1:00	13.1	13	0	0	12.3	15.4	16.1	15.9	15.9	15.7	16.3	16.2	16.7						
2/27/97 2:00	13.2	13.1	0	0															
2/27/97 3:00	13.4	13.2	0	0	12.3	15.4	16.1	15.9	15.9	15.7	16.3	16.2	16.7						
2/27/97 4:00	13.5	13.3	0	0															
2/27/97 5:00	13.7	13.4	0	0															
2/27/97 6:00	13.6	13.5	0	0	12.5	15.7	16.4	16.3	16.3	15.9	16.6	16.6	16.9						
2/27/97 7:00	13.4	13.3	0	0															
2/27/97 8:00	13.2	13.1	0	0															
2/27/97 9:00	13.2	12.9	0	0	11.8	15.9	16.7	16.8	16.6	16.2	17	17	17.4						
2/27/97 10:00	13	12.8	0	0															
2/27/97 11:00	12.9	12.8	0	0															
2/27/97 12:00	12.8	12.7	0	0	11.7	16.1	17	17.3	16.8	16.4	17.3	17.5	17.7						
2/27/97 13:00	12.7	12.7	0	0															
2/27/97 14:00	12.6	12.7	0	0															
2/27/97 15:00	12.7	12.7	0	0	11.7	16.4	17.4	17.7	17.2	16.7	17.7	17.9	18						
2/27/97 16:00	12.9	12.8	0	0															
2/27/97 17:00	13.1	12.9	0	0															
2/27/97 18:00	13.2	13	0	0	12.2	16.6	17.7	18.1	17.5	16.9	18	18.3	18.3						
2/27/97 19:00	13.1	12.9	0	0															
2/27/97 20:00	13	12.8	0	0															
2/27/97 21:00	12.8	12.7	0	0	11.6	16.8	18	18.6	17.8	17.1	18.4	18.8	18.7						
2/27/97 22:00	12.9	12.8	0	0															
2/27/97 23:00	12.9	12.9	0	0															
2/28/97 0:00	13	13	0	0	12.1	17	18.4	19	18.1	17.4	18.7	19.3	19	12.4	11.7	13.5	17.1	20.4	
2/28/97 1:00	15.7	12.9	0	0															
2/28/97 2:00	15.9	12.8	0	0															
2/28/97 3:00	16.1	12.8	0	0	11.7	17.3	18.7	19.5	18.4	17.6	19.1	19.8	19.3						
2/28/97 4:00	16.4	12.8	0	0															
2/28/97 5:00	16.8	12.9	0	0															
2/28/97 6:00	17.2	12.9	0	0	11.8	17.4	19.1	20	18.7	17.8	19.4	20.2	19.5						
2/28/97 7:00	17.5	12.8	0	0															
2/28/97 8:00	17.9	12.7	0	0															
2/28/97 9:00	18.2	12.7	0	0	11.5	17.7	19.5	20.5	19	18.1	19.8	20.7	19.9						
2/28/97 10:00	18.4	12.6	0	0															

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2/28/97 11:00	18.5	12.6	0	11.6	17.9	19.8	21	19.3	18.3	20.1	21.2	20.2							
2/28/97 12:00	18.7	12.6	0																
2/28/97 13:00	18.8	12.5	0																
2/28/97 14:00	18.9	12.4	0																
2/28/97 15:00	19.1	12.3	0	11.2	18.1	20.2	21.5	19.6	18.5	20.5	21.7	20.4							
2/28/97 16:00	19.2	12.4	0																
2/28/97 17:00	19.4	12.5	0																
2/28/97 18:00	19.5	12.6	0	11.9	18.3	20.5	22	19.8	18.7	20.9	22.2	20.8							
2/28/97 19:00	19.6	12.7	0																
2/28/97 20:00	19.6	12.8	0																
2/28/97 21:00	19.7	12.9	0	12.1	18.5	20.9	22.6	20.2	18.9	21.2	22.7	21							
2/28/97 22:00	19.7	13	0																
2/28/97 23:00	19.8	13.1	0																
3/1/97 0:00	19.7	13.2	0	12.3	18.8	21.3	23.1	20.5	19.2	21.6	23.3	21.4	10.3	9.6	12.1	16	20.1		
3/1/97 1:00	19.8	13.3	0																
3/1/97 2:00	19.9	13.4	0																
3/1/97 3:00	20	13.4	0	12.5	19	21.7	23.7	20.8	19.4	22	23.9	21.8							
3/1/97 4:00	20.1	13.3	0																
3/1/97 5:00	20.3	13.2	0																
3/1/97 6:00	20.4	13.2	0	12.1	19.3	22.1	24.3	21.2	19.7	22.4	24.4	21.9							
3/1/97 7:00	20.5	13.1	0																
3/1/97 8:00	20.7	13	0																
3/1/97 9:00	20.8	12.8	0	11.6	19.5	22.5	24.8	21.5	19.9	22.8	25	22.4							
3/1/97 10:00	20.9	13	0																
3/1/97 11:00	20.9	13.2	0																
3/1/97 12:00	21	13.5	0	12.7	19.7	22.9	25.4	21.8	20.1	23.2	25.5	22.7							
3/1/97 13:00	21.1	13.6	0																
3/1/97 14:00	21.3	13.7	0																
3/1/97 15:00	21.4	13.8	0	12.8	20	23.3	26	22.2	20.4	23.6	26.1	23							
3/1/97 16:00	21.5	13.9	0																
3/1/97 17:00	21.8	14	0																
3/1/97 18:00	21.9	14.1	0	13.2	20.3	23.8	26.6	22.6	20.6	24	26.7	23.3							
3/1/97 19:00	22.1	14.2	0																
3/1/97 20:00	22.2	14.2	0																

3/1/97 21:00	22.4	14.3	0	13.3	20.6	24.3	27.3	23	20.9	24.5	27.3	23.9					
3/1/97 22:00	22.5	14.4	0														
3/1/97 23:00	22.6	14.5	0														
3/2/97 0:00	22.7	14.5	0	13.3	20.9	24.7	27.9	23.5	21.2	24.9	27.9	24.4					
3/2/97 1:00	22.8	14.4	0														
3/2/97 2:00	22.9	14.3	0														
3/2/97 3:00	22.9	14.2	0	13.3	21.2	25.2	28.6	24	21.5	25.4	28.6	24.9					
3/2/97 4:00	23	14.1	0														
3/2/97 5:00	23	14	0														
3/2/97 6:00	23.2	13.9	0	12.8	21.4	25.6	29.2	24.6	21.8	25.8	29.1	25.3					
3/2/97 7:00	23.3	13.8	0														
3/2/97 8:00	23.5	13.7	0														
3/2/97 9:00	23.6	13.6	0	13.5	21.6	25.9	29.7	25	22.1	26.1	29.6	25.9					
3/2/97 10:00	23.7	13.6	0														
3/2/97 11:00	23.9	13.5	0														
3/2/97 12:00	24.1	13.5	0	13.6	21.9	26.4	30.3	25.4	22.3	26.5	30.2	26.1					
3/2/97 13:00	24	13.4	0														
3/2/97 14:00	24.3	13.3	0														
3/2/97 15:00	24.4	13.2	0	13.1	22.2	26.8	30.9	25.8	22.6	26.9	30.3	26.4					
3/2/97 16:00	24.5	13.2	0														
3/2/97 17:00	24.5	13.1	0														
3/2/97 18:00	24.7	13.2	0	13	22.5	27.1	31.4	26.2	22.8	27.2	31.3	26.9					
3/2/97 19:00	24.7	13.1	0														
3/2/97 20:00	24.8	13	0														
3/2/97 21:00	24.9	12.9	0	12.8	22.7	27.5	32	26.6	23.1	27.5	31.8	27					
3/2/97 22:00	24.8	13.1	0														
3/2/97 23:00	24.9	13.3	0														
3/3/97 0:00	25.1	13.5	0	13	22.9	27.8	32.5	26.9	23.3	27.8	32.3	27.8	6.8	3.5	6.2	12.2	19.9
3/3/97 1:00	25.2	13.7	0														
3/3/97 2:00	25.4	13.8	0														
3/3/97 3:00	25.5	14.1	0	13	23.1	28.1	33	27.3	23.5	28.1	32.8	28.1					
3/3/97 4:00	25.7	14.2	0														
3/3/97 5:00	25.8	14.1	0														
3/3/97 6:00	25.9	13.9	0	13.1	23.3	28.5	33.6	27.6	23.7	28.4	33.3	28.4					

3/4/97 17:00	30.7	13	0	0	12	25.3	30.9	37.3	31.9	25.9	30.7	36.6	33						
3/4/97 18:00	30.7	13	0	0	12														
3/4/97 19:00	30.8	13	0	0															
3/4/97 20:00	30.8	13.1	0	0															
3/4/97 21:00	30.8	13.2	0	0	12	25.3	30.9	37.5	32.2	25.9	30.7	36.8	33.1						
3/4/97 22:00	30.9	13.1	0	0															
3/4/97 23:00	30.9	13	0	0															
3/5/97 0:00	43.3	31.1	13	0	11.6	25.3	31	37.4	32.4	26	30.8	36.8	33.2	6.7	3.8	0.9	13.3	20.8	
3/5/97 1:00	31.2	12.8	0	0															
3/5/97 2:00	31.2	12.6	0	0															
3/5/97 3:00	31.3	12.4	0	0	11.3	25.4	31	37.3	32.6	26	30.8	36.6	33.3						
3/5/97 4:00	31.4	12.3	0	0															
3/5/97 5:00	31.5	12.2	0	0															
3/5/97 6:00	31.5	12.1	0	0	11.1	25.4	31.1	37.2	32.7	26.1	30.9	36.5	33.5						
3/5/97 7:00	31.5	12	0	0															
3/5/97 8:00	31.4	11.8	0	0															
3/5/97 9:00	31.5	11.9	0	0	11	25.4	31.1	37.1	32.7	26.1	30.9	36.4	33.6						
3/5/97 10:00	31.6	11.9	0	0															
3/5/97 11:00	31.7	12	0	0															
3/5/97 12:00	31.8	12.1	0	0	11	25.4	31	37.1	32.8	26.1	30.9	36.4	33.6						
3/5/97 13:00	31.9	12.2	0	0															
3/5/97 14:00	31.9	12.1	0	0															
3/5/97 15:00	32	12	0	0	11.1	25.4	31	37.2	32.9	26.1	30.8	36.4	33.7						
3/5/97 16:00	32	12.1	0	0															
3/5/97 17:00	32.2	12.1	0	0															
3/5/97 18:00	32.3	12	0	0	11.2	25.3	30.9	37.3	33	26.1	30.7	36.5	33.7						
3/5/97 19:00	32.4	12.1	0	0															
3/5/97 20:00	32.5	12.1	0	0															
3/5/97 21:00	32.7	12	0	0	11.1	25.3	30.8	37.2	33	26.1	30.7	36.5	33.8						
3/5/97 22:00	32.8	14.5	0	0															
3/5/97 23:00	33.1	15.7	0	0															
3/6/97 0:00	43	33.2	16.8	0	15.4	25.4	30.9	37.3	33.2	26.2	30.7	36.4	34.1	8.8	6.6	4.9	15.7	20.8	
3/6/97 1:00	33.1	15.6	0	0															
3/6/97 2:00	33	15.2	0	0															

3/6/97 3:00	33.2	15.1	0	13.3	25.3	30.8	37.3	33.2	26.1	30.7	36.5	34.2							
3/6/97 4:00	33.1	15	0																
3/6/97 5:00	33.2	14.8	0																
3/6/97 6:00	33.3	14.5	0	13.1	25.2	30.8	37.4	33.3	26.1	30.7	36.6	34.3							
3/6/97 7:00	33.3	14.3	0																
3/6/97 8:00	33.4	14.4	0																
3/6/97 9:00	33.6	14.3	0	13.2	25.3	30.8	37.6	33.4	26.1	30.7	36.8	34.4							
3/6/97 10:00	33.4	14.1	0																
3/6/97 11:00	33.3	14	0																
3/6/97 12:00	33.6	13.8	0	12.5	25.3	30.9	37.5	33.5	26.1	30.8	36.7	34.5							
3/6/97 13:00	33.7	13.7	0																
3/6/97 14:00	33.8	13.9	0																
3/6/97 15:00	33.9	14	0	13	25.4	30.9	37.5	33.6	26.2	30.9	36.7	34.6							
3/6/97 16:00	34	14.1	0																
3/6/97 17:00	34	14.2	0																
3/6/97 18:00	33.7	14.2	0	13.3	25.4	31	37.6	33.7	26.3	30.9	36.8	34.7							
3/6/97 19:00	33.9	14.3	0																
3/6/97 20:00	34.1	14.4	0																
3/6/97 21:00	34.2	14.5	0	13.6	25.5	31	37.7	33.8	26.4	31	36.9	34.8							
3/6/97 22:00	34.2	14.6	0																
3/6/97 23:00	34.3	14.5	0																
3/7/97 0:00	34.2	14.4	0	13.5	25.5	31.1	37.8	33.9	26.4	31.1	37	34.9	8.1	5.5	2	20.8			
3/7/97 1:00	34.4	14.5	0																
3/7/97 2:00	34.3	14.6	0																
3/7/97 3:00	34.4	14.5	0	13.7	25.6	31.2	37.8	34	26.5	31.2	37	35							
3/7/97 4:00	34.4	14.5	0																
3/7/97 5:00	34.5	14.5	0																
3/7/97 6:00	34.6	14.6	0	13.6	25.7	31.3	37.8	34.1	26.6	31.3	37	35							
3/7/97 7:00	34.7	14.6	0																
3/7/97 8:00	34.6	14.5	0																
3/7/97 9:00	34.3	14.6	0	13.6	25.8	31.4	37.8	34.2	26.7	31.4	37	35.1							
3/7/97 10:00	34.1	14.4	0																
3/7/97 11:00	33.9	14.2	0																
3/7/97 12:00	33.8	14	0	12.7	25.9	31.5	37.7	34.2	26.8	31.5	37	35.1							

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3/8/97 23:00	36.5	13.3	0	12.8	27.1	35.1	42.3	37	27.6	35.1	41.9	38.3
3/9/97 0:00	36.4	13.5	0									
3/9/97 1:00	36.8	13.9	0									
3/9/97 2:00	36.9	14.2	0									
3/9/97 3:00	37.1	14.5	0	13.7	27.2	35.6	43.1	37.6	27.8	35.5	42.7	38.9
3/9/97 4:00	37	14.9	0									
3/9/97 5:00	36.9	15	0									
3/9/97 6:00	37.3	15.1	0	14.1	27.4	36.1	43.9	38.2	28	36	43.5	39.5
3/9/97 7:00	37.5	15.2	0									
3/9/97 8:00	37.7	15.3	0									
3/9/97 9:00	37.8	15.4	0	14.4	27.6	36.6	44.7	38.8	28.2	36.5	44.3	40.1
3/9/97 10:00	38.2	15.5	0									
3/9/97 11:00	38.5	15.2	0									
3/9/97 12:00	38.4	15.1	0	14.2	27.9	37.1	45.5	39.4	28.5	36.9	45	40.8
3/9/97 13:00	38.3	15.1	0									
3/9/97 14:00	38.5	14.9	0									
3/9/97 15:00	38.7	14.8	0	13.8	28.2	37.6	46.2	40	28.7	37.4	45.7	41.4
3/9/97 16:00	38.8	14.6	0									
3/9/97 17:00	38.7	14.4	0									
3/9/97 18:00	38.6	14.2	0	13.3	28.5	38.1	46.9	40.5	29	37.8	46.4	41.9
3/9/97 19:00	38.5	14.1	0									
3/9/97 20:00	38.4	14.1	0									
3/9/97 21:00	38.3	14	0	13	28.8	38.6	47.5	41	29.2	38.2	47	42.4
3/9/97 22:00	38.2	13.9	0									
3/9/97 23:00	38.1	13.8	0									
3/10/97 0:00	38.5	13.9	0	13	29.1	39	48.1	41.4	29.5	38.6	47.5	42.8
3/10/97 1:00	38.6	13.7	0									
3/10/97 2:00	39.1	13.9	0									
3/10/97 3:00	39.4	14	0	13.2	29.4	39.5	48.6	41.8	29.7	38.9	48	43.3
3/10/97 4:00	39.5	14.1	0									
3/10/97 5:00	39.7	14	0									
3/10/97 6:00	39.9	14.1	0	13.2	29.7	39.9	49.1	42.1	29.9	39.3	48.4	43.6
3/10/97 7:00	40.2	14.1	0									
3/10/97 8:00	40.4	14	0									

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3/11/97 19:00	42.8	13.9	0.1	13	33	43.8	52.8	42.8	33	43	52	44.4							
3/11/97 20:00	43.1	14	0.1																
3/11/97 21:00	43.3	14.1	0	13	33	43.8	52.8	42.8	33	43	52	44.4							
3/11/97 22:00	43.2	14.1	0																
3/11/97 23:00	43.3	14	0																
3/12/97 0:00	43.6	14.1	0	13.2	33.2	44.1	53	42.7	33.2	42.3	52.1	44.3							
3/12/97 1:00	43.5	14.3	0																
3/12/97 2:00	43.7	14.4	0																
3/12/97 3:00	43.1	14.5	0	13.5	33.5	44.3	53.1	42.6	33.5	43.5	52.3	44.2							
3/12/97 4:00	42.9	14.6	0																
3/12/97 5:00	43.5	14.5	0																
3/12/97 6:00	43.2	14.7	0.1	13.8	33.7	44.6	53.3	42.5	33.8	43.8	52.4	44.1							
3/12/97 7:00	43.1	14.6	0.1																
3/12/97 8:00	42.9	14.5	0.1																
3/12/97 9:00	42.8	14.7	0	13.7	34	44.8	53.4	42.4	34	44	52.5	44							
3/12/97 10:00	43.1	14.5	0																
3/12/97 11:00	43	14.1	0.1																
3/12/97 12:00	42.8	14	0	12.9	34.3	45	53.6	42.3	34.3	44.3	52.7	43.9							
3/12/97 13:00	42.7	14	0.1																
3/12/97 14:00	42.7	13.8	0.1																
3/12/97 15:00	42.5	13.7	0.1	12.6	34.5	45.3	53.7	42.1	34.5	44.5	52.9	43.8							
3/12/97 16:00	42.7	13.8	0.1																
3/12/97 17:00	42.8	13.9	0.1																
3/12/97 18:00	42.7	14	0.1	13.1	34.8	45.5	53.9	42	34.8	44.7	53	43.7							
3/12/97 19:00	42.8	13.9	0																
3/12/97 20:00	42.6	13.9	0.1																
3/12/97 21:00	42.5	14	0.1	13.1	35	45.7	54	41.9	35	44.9	53.1	43.6							
3/12/97 22:00	42.2	14.2	0																
3/12/97 23:00	41.9	14.5	0																
3/13/97 0:00	42.1	14.7	0.1	13.8	35.2	45.9	54.1	41.7	35.3	45.1	53.2	43.4							
3/13/97 1:00	42.5	14.9	0.1																
3/13/97 2:00	42.7	15	0.1																
3/13/97 3:00	42.5	15.2	0																
3/13/97 4:00	42.1	15.4	0																

41

20

19.2

16.5

13.2

3/13/97 5:00	42.3	15.7	0	14.6	35.6	46.3	54.3	41.5	35.8	45.6	53.4	43.2
3/13/97 6:00	42.5	15.8	0.1									
3/13/97 7:00	41.9	15.9	0.1									
3/13/97 8:00	41.7	16.2	0.1									
3/13/97 9:00	42	16.4	0.1									
3/13/97 10:00	41.7	16.6	0									
3/13/97 11:00	41.5	16.8	0									
3/13/97 12:00	41.9	16.9	0	15.7	36.4	46.8	54.6	41.3	36.5	46.1	53.7	43
3/13/97 13:00	41.7	17	0.1									
3/13/97 14:00	41.8	17.1	0.1									
3/13/97 15:00	41.6	17	0.1									
3/13/97 16:00	41.2	16.9	0.1									
3/13/97 17:00	41.7	16.8	0.1									
3/13/97 18:00	41.4	16.7	0.1	15.8	37.2	47.3	54.9	41.2	37.2	46.6	54	42.8
3/13/97 19:00	41.1	16.8	0.1									
3/13/97 20:00	41.5	16.9	0.1									
3/13/97 21:00	41.6	17	0.1									
3/13/97 22:00	41.6	17.2	0.1									
3/13/97 23:00	41.8	17.1	0.1									
3/14/97 0:00	41.6	17	0.1	16	37.9	47.8	55.1	41	38	47.1	54.3	42.6
3/14/97 1:00	41.6	16.9	0.1									
3/14/97 2:00	41.3	16.5	0.1									
3/14/97 3:00	40.9	16.1	0									
3/14/97 4:00	40.9	15.8	0									
3/14/97 5:00	41.2	15.7	0									
3/14/97 6:00	40.8	15.3	0.1	14.7	38.6	48.2	55.4	40.7	38.6	47.5	54.5	42.4
3/14/97 7:00	40.6	15.1	0.1									
3/14/97 8:00	40.3	14.9	0.1									
3/14/97 9:00	40.2	14.6	0.1									
3/14/97 10:00	40.1	14.7	0.1									
3/14/97 11:00	40.5	14.6	0.1									
3/14/97 12:00	40.1	15.1	0.1	13.9	39	48.5	55.6	40.2	39	47.7	54.7	42
3/14/97 13:00	39.9	15.3	0.1									
3/14/97 14:00	39.8	15.9	0.2									

3/16/97 1:00	40.8	18.9	0.1	18.3	42.6	50.9	57	39.4	42.2	49.9	56	41.6
3/16/97 2:00	40.8	18.8	0									
3/16/97 3:00	40.7	18.7	0.1									
3/16/97 4:00	40.5	18.9	0.1									
3/16/97 5:00	40.3	18.7	0									
3/16/97 6:00	40.3	18.7	0	18.3	42.6	50.9	57	39.4	42.2	49.9	56	41.6
3/16/97 7:00	40.4	18.6	0									
3/16/97 8:00	40.2	18.7	0.1									
3/16/97 9:00	40.1	18.6	0.1									
3/16/97 10:00	40.2	18.5	0.1									
3/16/97 11:00	40.3	18.4	0.1									
3/16/97 12:00	40.4	18.3	0.1	17.8	42.8	51	57.1	39.3	42.3	49.9	56.1	41.5
3/16/97 13:00	40.2	18.1	0									
3/16/97 14:00	40.1	18.2	0.1									
3/16/97 15:00	40	18.3	0.1									
3/16/97 16:00	39.3	18.2	0.1									
3/16/97 17:00	40.1	18.1	0.1									
3/16/97 18:00	40.2	18.1	0.1	17.6	42.8	51	57.1	39.2	42.3	49.9	56.2	41.4
3/16/97 19:00	40.1	18.3	0.1									
3/16/97 20:00	39.9	18.4	0.1									
3/16/97 21:00	39.8	18.4	0.1									
3/16/97 22:00	39.7	18.3	0.1									
3/16/97 23:00	40	18.4	0.1									
3/17/97 0:00	39.6	18.5	0.1	17.7	42.7	51	57.1	38.9	42.2	49.8	56.2	41.1
3/17/97 1:00	39.7	18.5	0.2									
3/17/97 2:00	39.5	18.4	0.1									
3/17/97 3:00	39.4	18.4	0.1									
3/17/97 4:00	39.6	18.3	0									
3/17/97 5:00	39.2	18.3	0.1									
3/17/97 6:00	39.1	18.2	0.1	17.5	42.6	50.9	57	38.6	42.1	49.7	56.2	40.9
3/17/97 7:00	39.4	18.3	0.1									
3/17/97 8:00	39.2	18.4	0.1									
3/17/97 9:00	39.5	18.3	0.1									
3/17/97 10:00	39.3	18.3	0.1									

3/17/97 11:00	39.2	18.3	0.1	17.6	42.6	50.9	57	38.3	42	49.6	56.1	40.6							
3/17/97 12:00	39.1	18.4	0.1	17.6	42.6	50.9	57	38.3	42	49.6	56.1	40.6							
3/17/97 13:00	39	18.3	0.1																
3/17/97 14:00	38.9	18.3	0.1																
3/17/97 15:00	39.1	18.1	0.1																
3/17/97 16:00	38.9	17.7	0.1																
3/17/97 17:00	38.7	17.3	0.1																
3/17/97 18:00	38.8	16.8	0.1	15.9	42.6	50.8	56.9	37.9	41.8	49.4	56.1	40.3							
3/17/97 19:00	38.6	16.7	0.1																
3/17/97 20:00	38.5	16.5	0.1																
3/17/97 21:00	38.3	17.2	0.1																
3/17/97 22:00	38.1	17.4	0																
3/17/97 23:00	37.9	17.5	0																
3/18/97 0:00	38.1	17.6	0	16.5	42.3	50.6	56.8	37.6	41.5	49.2	55.9	40							
3/18/97 1:00	37.8	17.9	0																
3/18/97 2:00	37.9	18.1	0																
3/18/97 3:00	38	18.3	0																
3/18/97 6:00				17.9	42.1	50.4	56.6	37.4	41.4	49	55.7	39.7							
3/18/97 12:00				19.4	42.1	50.3	56.4	37.1	41.4	49	55.6	39.5							
3/18/97 18:00				18.2	42.1	50.3	56.3	36.6	41.4	48.9	55.5	39.1							
3/19/97 0:00				18.1	42.1	50.2	56.2	36.1	41.3	48.8	55.4	38.7							
3/19/97 6:00				18.1	41.9	50	56.1	35.6	41.1	48.6	55.2	38.4							
3/19/97 12:00				17.6	41.8	49.9	56	35.2	40.9	48.4	55.1	37.9							
3/19/97 18:00				16.2	41.6	49.6	55.8	34.8	40.7	48.2	54.9	37.5							
3/19/97 22:00														18.9	16.8	15.9			19.8
3/21/97 0:00				15	39.5	47.1	54.1	35.8			55.1								
3/21/97 6:00				15.6	39.1	46.7	53.8	35.4			54.7								
3/21/97 12:00				15.8	38.7	46.2	53.5	35			54.3								
3/21/97 18:00				15.1	38.3	45.9	53.1	34.4			54								
3/22/97 0:00				15.5	37.8	45.4	52.7	33.8			53.6								
3/22/97 6:00				16	37.6	45.2	52.3	33.9			53.2								
3/22/97 12:00				16.2	37.4	44.9	51.9	33.3			52.8								
3/22/97 18:00				15.7	37.1	44.6	51.6	32.6			52.5								
3/23/97 0:00				16	36.8	44.2	51.2	32			52.2								

3/23/97 6:00	15.9	36.5	43.8	50.8	31.4	51.7						
3/23/97 12:00	15.1	36.2	43.5	50.4	31.1	51.3						
3/23/97 18:00	16.2	35.8	43.1	49.9	30.5	50.8						
3/24/97 0:00	17.4	35.6	42.8	49.4	30.3	50.3						
3/24/97 6:00	15.8	35.4	42.5	49.1	29.9	49.9						
3/24/97 12:00	16	35.1	42.2	48.6	29.4	49.5						
3/24/97 18:00	16.4	34.8	41.8	48.1	29.1	49						
3/25/97 0:00	16.3	34.5	41.4	47.6	28.6	48.6						
3/25/97 6:00	16.1	34.2	41.1	47.1	28.2	48						
3/25/97 12:00	16.7	34	40.8	46.6	27.9	47.4						
3/25/97 18:00	17	33.8	40.5	46.1	28	47						
3/26/97 0:00	15.9	33.6	40.2	45.6	27.6	46.4						
3/26/97 6:00	16	33.3	39.9	45.2	27.3	45.8						
3/26/97 12:00	15.1	33	39.5	44.7	27.5	45.4						
3/26/97 18:00	14.7	32.5	39	44.2	27.2	44.9						
3/26/97 22:00							19.3	18.7	16.2	20.4		
3/27/97 0:00	14.3	32	38.4	43.7	26.8	44.4						
3/27/97 6:00	14.4	31.5	37.9	43.2	26.8	43.9						
3/27/97 12:00	14.5	31	37.4	42.7	26.6	43.3						
3/27/97 18:00	14.3	30.5	36.8	42.2	26.3	42.8						
3/28/97 0:00	14.5	30.1	36.3	41.6	26.1	42.2						
3/28/97 6:00	16.4	29.8	36	41.1	26.7	41.6						
3/28/97 12:00	17.5	29.7	35.7	40.6	26.7	41.1						
3/28/97 18:00	18.7	29.7	35.5	40.2	26.5	40.3						
3/29/97 0:00	20.2	29.8	35.3	39.8	26.5	40.4						
3/29/97 6:00	20.1	30.1	35.4	39.6	26.9	40.1						
3/29/97 12:00	19.9	30.5	35.5	39.4	27	39.9						
3/29/97 18:00	20.6	30.9	35.6	39.3	27	39.8						
3/30/97 0:00	21.9	31.1	35.8	39.2	27.1	39.8						
3/30/97 6:00	21.9	31.6	36	39.3	27.3	39.7						
3/30/97 12:00	21.8	31.8	36.1	39.3	27.2	39.8						
3/30/97 18:00	21.6	32.1	36.3	39.4	27	39.9						
3/31/97 0:00	22.4	32.3	36.5	39.4	27	40						
3/31/97 6:00	22.7	32.6	36.7	39.6	27.1	40.2						

Michigan State University - Compost Aeration Experiment: Trial #4, Bulk Density

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Total Mass and Bulk Density of raw materials

Date: 2/25/97

Weight of drum = 17.8 lb

Total mass= 397 lb

Total mass= 180.24 kg

Area chamber= 0.2917 m²

Length chamber= 1.2192 m

Volume chamber= 0.3557 m³

Density= 506.77 kg/m³

Total Mass and Bulk Density of composting material

Date: 4/1/97

	Layer Thickness	Layer Volume			Layer Bulk Density
Height(in)	(m)	(m ³)	Wt(lb)	Wt(kg)	(kg/m ³)
30"-37"	0.1778	0.0519	76.6	34.776	670.492
24"-30"	0.1524	0.0445	75.6	34.322	772.028
18"-24"	0.1524	0.0445	87	39.498	888.445
0"-18"	0.4572	0.1334	136.8	62.107	465.668

Total Bulk Density= 622.66 kg/m³

Michigan State University - Compost Aeration Experiment: Trial #4, Moisture

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Moisture content: Raw Materials

2/25/97

Tin#	ID#	Tin Wt. (g)	Wet Wt (g)	Dry Wt (g)	MC(%)
B1	0"-12"	148.33	425.3	250.43	63.136802
	2 13"-38"	148.37	517.6	286.21	62.668256
	1 38"-48"	145.92	406.9	235.29	65.755997

Moisture Content: Permeability Material

4/1/97

Tin#	ID#	Tin Wt. (g)	Wet Wt (g)	Dry Wt (g)	MC(%)
B1	0"-18"	148.36	305	220.46	53.970889

APPENDIX B
ORGANIC MATTER RAW DATA

Michigan State University - Compost Aeration Experiment: Trial #4 - Organic Matter

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Trial #4 - Turn 0

Date taken: 2/5/97

Sample ID	Crucible Wt (g)	Dry + Crucible Wt (g)	Ash + Crucible Wt (g)	Dry Wt (g)	Ash Wt (g)	OM (g)	OM Content %
Initial							
02597a	25.0620	29.4462	26.3722	4.3842	1.3102	3.0740	70.12
02597b	24.7765	29.2591	25.9665	4.4826	1.1900	3.2926	73.45
02597c	21.3666	26.1767	23.2858	4.8101	1.9192	2.8909	60.10
				Average=		3.0858	67.89
				Std Dev=		0.2011	6.95

Date taken: 6/23/98

Sample ID	Crucible Wt (g)	Dry + Crucible Wt (g)	Ash + Crucible Wt (g)	Dry Wt (g)	Ash Wt (g)	OM (g)	OM Content %
Final							
AT4	24.7660	29.3841	27.2125	4.6181	2.4465	2.1716	47.02
3a	25.0088	30.1472	27.6511	5.1384	2.6423	2.4961	48.58
7a	24.7802	29.4813	27.1080	4.7011	2.3278	2.3733	50.48
				Average=		2.3470	48.69
				Std Dev=		0.1638	1.73

APPENDIX C
PERMEABILITY RAW DATA

Michigan State University - Compost Aeration Experiment: Trial #3, 1 Turn

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Permeability Measurements - Trial 3

Bulk Density #1, Rep #1

Density = 392.53264 kg/m³

Date: 12/14/96

Velocity (ball)	Velocity (ml/min)	Velocity (cm ³ /min)	Press diff (in)	Velocity (m/s)	dP (Pa)	x dP/L (Pa/m)	y Velocity (m/s)	slope= K=
10	900	900	0.001	0.0004625	0.24828	0.8711579	0.0004625	2.14E-09 m ²
20	2000	2000	0.005	0.0010279	1.2414	4.3557895	0.0010279	2.14E-05 cm ²
30	3200	3200	0.009	0.0016446	2.23452	7.8404211	0.0016446	
40	4350	4350	0.016	0.0022356	3.97248	13.938526	0.0022356	
50	6050	6050	0.023	0.0031093	5.71044	20.036632	0.0031093	
60	7200	7200	0.028	0.0037004	6.95184	24.392421	0.0037004	
70	8900	8900	0.036	0.0045741	8.93808	31.361684	0.0045741	
80	10200	10200	0.048	0.0052422	11.91744	41.815579	0.0052422	
90	11600	11600	0.063	0.0059617	15.64164	54.882947	0.0059617	

Bulk Density #1, Rep #2

Density = 390.06287 kg/m³

Date: 12/14/96

Velocity (ball)	Velocity (ml/min)	Velocity (cm ³ /min)	Press diff (in)	Velocity (m/s)	dP (Pa)	x dP/L (Pa/m)	y Velocity (m/s)	slope= K=	y Velocity (m/s)	slope= K=
10	900	900	0.001	0.0004625	0.24828	0.8711579	0.0004625	0.0004625 K=	0.0004625	2.17E-09 m ²
20	2000	2000	0.005	0.0010279	1.2414	4.3557895	0.0010279	0.0010279 K=	0.0010279	2.17E-05 cm ²
30	3200	3200	0.009	0.0016446	2.23452	7.8404211	0.0016446	0.0016446	0.0016446	
40	4350	4350	0.015	0.0022356	3.7242	13.067368	0.0022356	0.0022356	0.0022356	
50	6050	6050	0.022	0.0031093	5.46216	19.165474	0.0031093	0.0031093	0.0031093	
60	7200	7200	0.027	0.0037004	6.70356	23.521263	0.0037004	0.0037004	0.0037004	

70	8900	8900	0.036	0.0045741	8.93808	31.361684	0.0045741	0.0045741	0.0045741
80	10200	10200	0.047	0.0052422	11.66916	40.944421	0.0052422	0.0052422	0.0052422
90	11600	11600	0.062	0.0059617	15.39336	54.011789	0.0059617	0.0059617	0.0059617
Permeability Measurements -Trial 3									
Bulk Density #2, Rep #1									
Density =			452.59682 kg/m^3			Chamber			
Date:			12/14/96			Dia = 0.2032 m			
Velocity (ball)			Velocity (ml/min)			Area = 0.0324293 m^2			
			Velocity (cm^3/min)			Length = 0.285 m			
			Press diff (in)			fluid viscosity = 2.04E-05 kg/m/s			
			Velocity (m/s)			x y			
			dP (Pa)			dP/L (Pa/m)			
			Press diff (in)			Velocity (m/s)			
			Velocity (m/s)			slope=			
			Press diff (in)			K=			
			Velocity (m/s)			K=			
			Press diff (in)			K=			
			Velocity (m/s)			K=			
			Press diff (in)			K=			
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			Press diff (in)			K=			
			Velocity (m/s)			K=			
			Press diff (in)			K=			

90 11600 11600 0.076 0.0059617 18.86928 66.208 0.0059617 0.0059617

Additional Permeability Measurements - Material from Trial #3 compost mixture (1:1 woodchip/diary manure)

Chamber Dimensions

Dia = 0.2032 m
Area = 0.0324128 m^2
Length = 0.285 m
fluid viscosity = 2.04E-05 kg/m/s

Description: Dry Bulk Density= 1.54E+02 kg/m^3
Date: 12/5/96
V(ball) V(ml/min) V(m/s) delta P (in) dP(Pa) Graphing x y1
15 1400 7.20E-04 0.001 0.24828 0.8711579 7.20E-04 slope= 0.0004735
30 3200 1.65E-03 0.004 0.99312 3.4846316 1.65E-03 intercept= 0.0004758
50 6100 3.14E-03 0.006 1.48968 5.2269474 3.14E-03 K= 9.66E-09 m^2
71 9000 4.63E-03 0.008 1.98624 6.9692632 4.63E-03 K= 9.66E-05 cm^2
96 12200 6.27E-03 0.015 3.7242 13.067368 6.27E-03 R-squared= 0.9414816

Description: Bulk Density= 1.80E+02 kg/m^3
Date: 12/13/96
V(ball) V(ml/min) V(m/s) delta P (in) dP(Pa) Graphing x y2
30 3200 1.65E-03 0.004 0.99312 3.4846316 1.65E-03 slope= 0.0002616
50 6100 3.14E-03 0.013 3.22764 11.325053 3.14E-03 intercept= 0.000502
71 9000 4.63E-03 0.019 4.71732 16.552 4.63E-03 K= 5.34E-09 m^2
96 12200 6.27E-03 0.024 5.95872 20.907789 6.27E-03 K= 5.34E-05 cm^2
R-squared= 0.9751302

Michigan State University - Compost Aeration Experiment: Trial #4, 0 Turn

Andrew Fogiel

Mixture: 1 part cow manure, 1 part wood chips

Permeability Measurements

Permeability Measurements				Chamber		Flow Meter	
				Dia =	0.2032 m	Dia =	0.009525 m
				Area =	0.0324293 m^2	Area =	7.13E-05 m^2
				Length =	0.3048 m		
Dry Density=				217.76185 kg/m^3	fluid viscosity = 2.04E-05 kg/m/s		
Date: 4/1/97							
Velocity (ball)	Velocity (ml/min)	Velocity (cm^3/min)	Press diff (in)	Velocity (m/s)	dP (Pa)	dP/L (Pa/m)	Velocity (m/s)
10	900	900	0.001	0.000463	0.24828	0.814567	0.000463
20	2000	2000	0.004	0.001028	0.99312	3.258268	0.001028
30	3200	3200	0.009	0.001645	2.23452	7.331102	0.001645
40	4350	4350	0.014	0.002236	3.47592	11.40394	0.002236
50	6050	6050	0.021	0.003109	5.21388	17.10591	0.003109
				K=		K=	
				0.000463		0.001028	
				slope=		slope=	
				0.0001584		3.23E-09 m^2	
						3.23E-05 cm^2	

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