พลังงานความร้อนที่เกิดขึ้นและการกระจายตัวของอุณหภูมิในกระบวนการทำปุ๋ยหมักแบบใช้อากาศ

ปูทอง รัตนมาลัย

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HEAT GENERATION AND TEMPERATURE DISTRIBUTION IN AN AEROBIC COMPOSTING PROCESS

Putong Ratanamalaya

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Thesis Title

HEAT GENERATION AND TEMPERATURE DISTRIBUTION IN AN AEROBIC COMPOSTING PROCESS

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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ปูทอง รัตนมาลัย : พลังงานความร้อนที่เกิดขึ้นและการกระจายตัวของอุณหภูมิในกระบวนการทำปุ๋ยหมักแบบใช้อากาศ
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การทำปุ๋ยหมักคือการทำของเสียให้เสถียรภาพที่ต้องการสภาวะแวดล้อมที่ดีที่สุดของอัตราส่วนคาร์บอนต่อไนโตรเจน, ความชื้น และการให้อากาศ เพื่อให้ผลเป็นอุณหภูมิเทอร์โมฟิลลิค ในการศึกษานี้พลังงานความร้อนที่เกิดขึ้นและการกระจายตัวของอุณหภูมิในกระบวนการทำปุ๋ยหมักแบบให้อากาศของขยะอินทรีย์ได้ถูกนำมาวิเคราะห์ การศึกษาของกระบวนการมีพื้นฐานมาจากการตรวจวัดอุณหภูมิที่เพิ่มขึ้นในกองปุ๋ยหมักกับอัตราการเป่าอากาศที่แตกต่าง โดยใช้ถังหมักทรงกระบอกสี่ใบ ขนาดเส้นผ่าศูนย์กลาง 0.5 ม. ยาว 1 ม. ประเภทเศษอาหารและเศษขยะจากสนามหญ้าตามบ้าน (เศษใบไม้และเศษหญ้า) ได้ถูกนำมาใช้ในอัตราส่วน 1:0.03 โดยน้ำหนักสำหรับ เศษอาหาร : เศษหญ้า เพื่อให้ได้อัตราส่วนของคาร์บอนต่อไนโตรเจนเท่ากับ 20-30:1 การให้อากาศเป็นไปตามทางยาวของถังผ่านท่อพีวีซีขนาดเส้นผ่าศูนย์กลาง ½ นิ้ว อัตราการเป่าอากาศของการทดลอง RUN I, II, III และ IV คือ 1.8, 3.6, 5.4 และ 10 ลบ.ม./วัน ตามลำดับ อุณหภูมิในกองปุ๋ยหมักได้เพิ่มขึ้นอย่างรวดเร็วในช่วง 1-3 วันแรก อุณหภูมิสูงสุดพบว่าอยู่ที่จุดกึ่งกลางของกองปุ๋ย ผลคือ 64 °ซ, 51.8 °ซ, 55.4 °ซ และ 58.9°ซ ในวันที่ 15, 20, 10 และ 9 สำหรับการทดลอง RUN I, II, III และ IV ตามลำดับ อุณหภูมิจะถึงที่สภาวะเสถียรภาพหลังจาก 24-35 วัน ค่าการนำความร้อนที่ใช้ในการศึกษาได้มาจากการทดลองของ ตัวอย่างปุ๋ยต่าง ๆ และค่าเฉลี่ยคือ 0.53 วัตต์/ม./°ซ ค่าการกระจายความร้อนที่คำนวณได้คือ 2×10^{-7} ตร.ม./วินาที explicit finite difference method ถูกนำมาใช้ร่วมกับสมการความร้อนหนึ่งมิติ ของ Fourier ในแนวรัศมีของวงกลม เพื่อที่จะหาแบบแผนทางคณิตศาสตร์สำหรับโปรแกรมคอมพิวเตอร์ พลังงานความร้อนที่เกิดขึ้นต่อหนึ่งหน่วยปริมาตร (วัตต์/ลบ.ม.) ได้ถูกประมาณคือ 133, 221.4, 242 และ 483.7 วัตต์/ลบ.ม. หรือ 2,080.5, 2,556.4, 3,958.1 และ 7,911.4 Btu/ชม.-กก. ของของแข็งระเหย สำหรับการทดลอง RUN I, II, III และ IV ตามลำดับ ผลการศึกษาบ่งชี้ว่าการกระจายตัวของอุณหภูมิและพลังงานความร้อนที่เกิดขึ้นระหว่างกระบวนการทำปุ๋ยหมักแบบใช้อากาศนั้น มีผลกระทบจากอัตราการเป่าอากาศ

สาขาวิศวกรรมสิ่งแวดล้อม ลายมือชื่อนักศึกษา...................................
ปีการศึกษา 2545 ลายมือชื่ออาจารย์ที่ปรึกษา..........................

PUTONG RATANAMALAYA: HEAT GENERATION AND TEMPERATURE DISTRIBUTION IN AN AEROBIC COMPOSTING PROCESS, THESIS ADVISOR : RANJNA JINDAL, Ph.D. 124 PP. ISBN 974-533-179-1

HEAT GENERATION/ TEMPERATURE DISTRIBUTION/
AEROBIC COMPOSTING/ THERMOPHILIC/ COMPOST QUALITY

Composting is a waste stabilization process that requires optimum operating conditions of C/N ratio, moisture, and aeration to achieve thermophilic-temperatures. In this study, heat generation and temperature distribution during the in-vessel aerobic composting of organic fractions of municipal solid waste were investigated. The process evaluations were based on monitoring temperature rise in composting mass with different aeration rates. Four insulated cylindrical composters with 0.5 m diameter and 1 m length were used. Food waste and household yard waste were mixed at a ratio of 1:0.03 by weight to obtain a C/N ratio of 20-30:1. Air was supplied length-wise to the central axis of the composters through ½” PVC pipes. Aeration rate provided for four experimental runs, RUN I, II, III and IV were 1.8, 3.6, 5.4 and 10 m^3/d, respectively. Rapid temperature rise during composting runs was found within the fist few days (1-3 days). The maximum temperatures detected at the center of the composting mass, were 64 ^{o}C, 51.8 ^{o}C, 55.4 ^{o}C and 58.9^{o}C on the 15th, 20th, 10th, and 9th day of RUN I, II, III and IV, respectively. The temperatures were stabilized (ambient temperature) after about 24-35 days. Thermal conductivity of the composted material was experimentally determined on the samples from different runs and the average was 0.53 W/m/^{o}C. The thermal diffusivity was calculated to be 2×10^{-7} m^2/s. A numerical scheme was developed by using explicit finite difference method with one-dimensional Fourier’s heat equation along radial directions. Maximum heat generated per unit volume during each run were estimated to be 133, 221.4, 242 and 483.7 W/m^3, thus, the maximum energy content were 2,080.5, 2,556.4, 3,958.1 and 7,911.4 Btu/hr-kg TVS for RUN I, II, III and IV, respectively. The results indicated that temperature profiles and heat generation during the aerobic composting process were influenced by aeration rates.

สาขาวิศวกรรมสิ่งแวดล้อม ลายมือชื่อนักศึกษา....................................
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List of Symbols and Abbreviations

α = Thermal diffusivity constant

A = The area of cross section through which heat flows

Btu = British thermal unit

c = Specific heat capacity by means of heat required to raise the temperature of unit mass (1 g) by 1 ^{o}C

$C_aH_bO_cN_d$ = Organic matter

C/N = Carbon to nitrogen ratio

CO_2 = Carbon dioxide

^{O}C = Degree Celsius

d = Diameter

ΔE = Change in internal energy of the system

^{O}F = Degree Fahrenheit

hr = Hour

h = Convection heat transfer coefficient

H_2O = Moisture, water

I = Current

k = Thermal conductivity of the medium

l = Length

m = Mass

N = Number of grids

n = Unit number

NH_3 = Ammonia

O_2 = Oxygen

q = Heat flow in the system

q_x = The rate at which heat enters the face located at x

q_V = heat flow in the system maintained at constant volume

$\overset{\circ}{q}$ = The heat generation per unit volume

Q_{air} = Air flow rate

r = Distance r

List of Symbols and Abbreviations (continued)

R = Radius

RQ = The respiratory quoteint

SO_4^{2-} = Sulfate

t = Time

T = Temperature

T_s = Surface temperature

T_∞ = Ambient fluid temperature

$\frac{\partial T}{\partial x}$ = Temperature gradient

TS = Total solids

TVS = Total volatile solids

$\forall$ = Volume

V = Voltage

W = watt

Chapter I
Introduction

1.1 Introduction

Composting has been utilized as means of organic resource recovery and it is widely adopted for the treatment disposal of solid waste. It is a natural biological process in the ecosystem applied to organic waste, generally to solid and semi-solid organic wastes. Blanc, et al. (1996) stated that composting is a self-heating, aerobic solid phase biodegradation process of organic waste materials, making possible its return to the environment as soil fertilizer and conditioner. Haug (1980, 1993) defined composting as the process of biological decomposition and stabilization of organic substrates, under conditions that allow development of optimum temperature for thermophilic organisms as a result of biologically produced heat, and to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Figure 1.1).

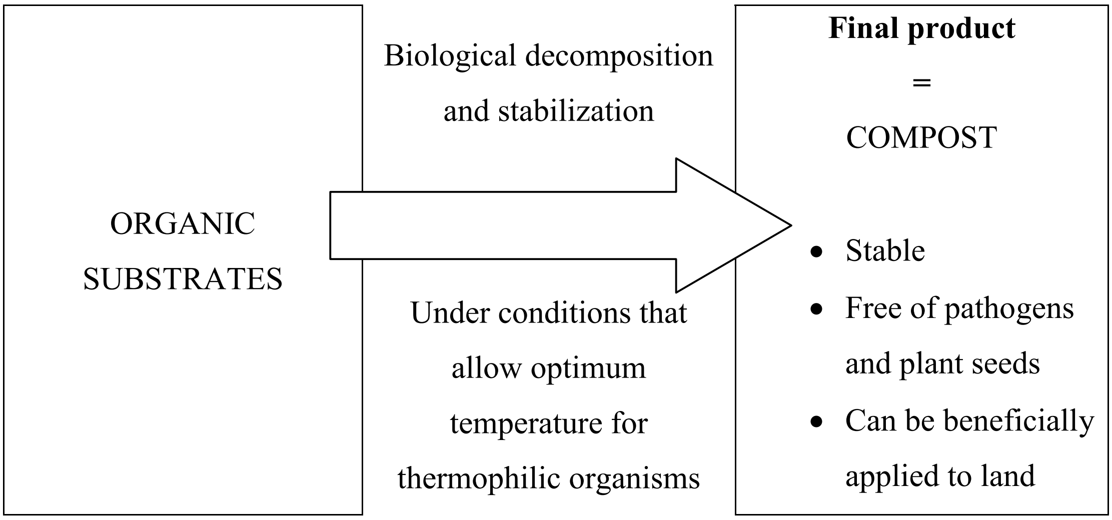


Figure 1.1 Composting definition

Aerobic composting is the decomposition of organic wastes in the presence of oxygen (air); with CO_2, NH_3, water and heat as the end products of biological metabolism (Polprasert, 1993). Theoretically, all organic matter could be broken down and escape as CO_2 and water, in which case finished compost, would consist of nothing but the remaining ash. The fact that this does not always happen, and that the remaining stable organic fraction is useful to soils and plants, is one of the reasons composting has such value.

There are several benefits of composting. It is a great recycler; it is more than a fertilizer, more than a soil conditioner; it provides and releases plant nutrients, protects against drought and stops nutrient loss from leaching. It builds good soil texture and structure, stops erosion and improves aeration. Compost products can alter acidity or alkalinity and also can stimulate plants growth (Devkota, 1984).

There are two types of composting based on oxygen requirements, namely, aerobic composting and anaerobic composting. Aerobic composting is the decomposition of organic substrates in the presence of oxygen (air), while anaerobic composting process undergoes without air. Unlike anaerobic composting, aerobic composting generates significantly higher amount of heat from decomposition of organic materials.

1.2 Statement of the Problem

Maintaining thermophilic temperatures is a primary requirement for pathogen inactivation and cyst destruction. When the temperatures exceed an organisms' optimal growth temperature, the organisms quickly come under severe stress. Temperatures slightly below the optimum can generally be tolerated better then temperatures slightly above the optimum ("The Biocycle Guide to In-vessle Composting", 1986). Thus, composting process requires special conditions of moisture and aeration to achieve thermophilic temperature. Such biological stabilization and conversion processes deal with dilute aqueous solutions, and only limited temperature evaluations are possible (Haug, 1993).

The basic objective of process control is to maximize microbial activity at the expense of the organic waste being treated. This is equivalent to maximizing metabolic heat output. In a self-heating ecosystem, temperature is both effect and cause. It is a function of the accumulation of heat generated metabolically, and simultaneously, temperature is a determinant of metabolic activity. The correlation between heat output and temperature is the centerpiece of rational control of the composting process (MacGregor, et al., 1981).

Heat evolution, occurring in proportion with microbial metabolism, is a fundamental means of observing the rate of composting activity in situ. The effect of various parameters on microbial activity can be quantified through monitoring the metabolic heat generation. In design and management of composting systems, heat management is the basis of temperature control (Miller, 1996). While the effect of temperature on composting is well understood, the kinetics and thermodynamics of heat evolution during the process are not fully investigated. It is worthy of investigation for both scientific and engineering reasons. Therefore, the relationship between heat generated and temperature distribution in forced aeration composting process should be studied. In addition, understanding the process maturation and stability of the remaining fraction is therefore of great significance (Brinton, et al., 1995).

1.3 Research Objectives

The overall aim of this study was to investigate the heat generation during an aerobic composting process, specific objectives included the following:

1.3.1 to investigate the temperature rise in aerobic composting of organic fractions of municipal solid wastes
1.3.2 to develop a numerical scheme for obtaining heat generation from temperature profiles
1.3.3 to estimate the heat generation from the experimental temperature profiles utilizing the developed numerical scheme
1.3.4 to evaluate the influence of air flow rate on heat generation and temperature profiles

1.4 Scope

To accomplish the above objectives following tasks were covered in the scope of this study:

1.4.1 modified insulated cylindrical composters were used for this study
1.4.2 aerobic composting process was carried out with the mixture of food waste collected from fresh food market, and household yard waste

1.4.3 chemical and physical characteristics determined for the composting mass constituents included: total solids (TS), moisture contents, volatile solids (VS), ash, carbon (C), nitrogen (N), C/N ratio, pH, thermal conductivity, and thermal diffusivity

1.4.4 experimental runs with different aeration rates were conducted

1.4.5 the numerical scheme was developed for heat generation in the composting mass

1.4.6 only one-dimensional relationship between the heat generation ($\overset{\circ}{q}$) and the temperature distribution ($\frac{\partial T}{\partial t}, \frac{\partial T}{\partial r}$) along radial direction was considered

1.4.7 Temperature profiles were simulated using the developed numerical scheme and compared with the experimental ones for $\overset{\circ}{q}$ estimation.

Chapter II
Literature Review

2.1 Composting

Composting process is currently viewed primarily as a waste management method to stabilize organic waste, such as manure, yard trimmings, municipal biosolids, and organic urban wastes. The stabilized end-product (compost) is widely used as a soil amendment to improve soil structure, provide plant nutrients, and facilitate the revegetation of disturbed or eroded soil (U.S.EPA, 1998). This process can be carried out on a large or small scale, with the management of optimum operating conditions.

In its simplest form, compostable material is arranged in long rows (windrows) and turned periodically to ensure good mixing. This process can handle large quantities of input, such as yard trimmings of up to 100,000 cubic yards per year, on only a few acres of land. Raw materials that tend to be very odorous during composting, such as municipal waste sludge (biosolids), can be processed in more elaborate systems and in a confined facility where odorous air can be treated. These systems use rotating drums, trenches, or enclosed tunnels for initial processing, followed by a covered curing period (U.S.EPA, 1998).

All composting methods share similar characteristic features and processes. Initially high microbial activity and heat production cause temperatures within the compostable material to rise rapidly into the thermophilic range (50 ^{o}C and higher). This temperature range is maintained by periodic turning or the use of controlled air flow. After the rapidly degradable components are consumed, temperatures gradually fall during the "curing" stage. At the end of this stage, the material is no longer self-heating, and the finished compost is ready for use. Substantial changes occur in microbial populations and species abundance during the various temperature stages. Mesophilic bacteria and fungi are dominant in the initial warming period, thermophilic bacteria (especially actinomycetes) during the high temperature phase, and mesophilic bacteria and fungi during the curing phase (U.S.EPA, 1998).

Aerobic composting process can be represented by following biochemical reaction (Tchobanoglous, Theisen, and Vigil, 1993):

$$\begin{matrix}\text{organic}\\\text{matter}\end{matrix} + O_2 + \text{nutrients} \xrightarrow{\text{microorganisms}} \begin{matrix}\text{new}\\\text{cells}\end{matrix} + \begin{matrix}\text{resistant}\\\text{organic}\\\text{matter}\end{matrix}$$

$$+ CO_2 + H_2O + NH_3 + SO_4^{2-} + \ldots + \text{heat} \qquad (2.1)$$

With empirical formula for mole composition of the organic material initially present in a composting pile and for complete conversion, the oxygen requirement may be calculated by the following equation (Tchobanoglous et al., 1993):

$$C_aH_bO_cN_d + \frac{4a + b - 2c + 3d}{4} O_2 \rightarrow aCO_2 + \frac{b - 3d}{2} H_2O + dNH_3 \qquad (2\text{-}2)$$

It can be seen from equations (2.1) and (2.2) that aerobic degradation requires

(a) oxygen,

(b) nutrients, and

(c) microorganisms.

The end products of composting process include:

(a) compost,

(b) gases,

(c) moisture, and

(d) energy.

According to Stentiford (1996), there are three principal factors to control during aerobic composting process, namely

(a) aeration

(b) temperature and

(c) moisture content.

The air could be supplied to a composting process by

(a) agitation, i.e., windrow composting,

(b) forced aeration, i.e., aerated static pile composting, and

(c) combination of agitation and forced aeration.

The required air flow rate could be controlled and monitored in the laboratory using appropriate instruments. The oxygen requirement depends on

(a) type of waste (nutrients, particle size, etc.),
(b) process conditions (moisture content, structures, etc.)
(c) process temperature, and
(d) stage of the process (higher requirements in the early stages).

The environmental temperature has an important effect on the survival and growth of microorganisms. Tchobanoglous et al., (1993) and Miller, (1991) defined temperature ranges for microbial growth and survival as shown in Table 2.1.

Table 2.1 **Typical temperature ranges for various bacteria**

Type	Temperature					
	Tchobanoglous, 1993				Miller, 1991	
	°C		°F		°C	°F
	Range	Optimum	Range	Optimum		
Psychophilic	-10-30	15	40-110	85	< 20	< 94
Mesophilic	20-50	35	94-150	120	> 40	>130
Thermophilic	45-75	55	140-193	157	> 45	>140

Note from Biological Degradation of Wastes (8) by Miller, C. F., 1991, and Integrated Solid Waste Management Engineering Principles and Management Issues (676) by Tchobanoglous, et al., 1993, (USA: McGraw-Hill, Inc.)

Quality of the compost product depends on the characteristics of the feed substrates, the design parameters of the high-rate and curing phases, the amount of pre-and postprocessing, and the operating conditions maintained within the system. A number of criteria can be established to define product quality. These include physical criteria such as particle size distribution, texture, color, odor, moisture content, and general appearance. Criteria can also be established o define compost stability or maturity. Specific oxygen consumption rate (mg O_2/kg volatile solid per hour), absence of toxic compounds, reduction of biodegradable volatile solids (BVS) across the system, and a return to near ambient temperatures at the end of the process can be used to measure compost stability. Criteria can also be established for the chemical characteristics of the compost. This might include the nutrient content, nitrate/ammonia ratio, absence readily degradable compounds such as starch, absence of anaerobic intermediates such as acetic acid, heavy metal content, and the effect on seed germination (Haug, 1993).

In general, U.S.EPA Part 503 rule for composting requires pathogens and vector attraction reduction (Switzenbaum et al., 1997). The physical stability of the end product of composting which is important for transporting, handling, storage and application, is assessed by:

(a) stabilized temperature/heat output,
(b) color,
(c) odor, and
(d) solid destruction.

There are various procedures recommended for compost stability assessment, both by direct and indirect measurement. Their assessment must be made based on the energy available for biological oxidation.

In order to control the composting process, microbially generated heat must be removed from a mass body. This is to prevent the temperature of the substrate, which is a good thermal insulator, from reaching levels inhibitive to the resident microbial population. The heat transfer mechanisms involved are convection and conduction, with radiation effects being assumed negligible (Shaw and Stentiford, 1996).

2.2 Thermodynamics

Thermodynamics is normally associated with heat, but the subject deals not only with heat but all forms of energy. Application of thermodynamic principles is a fundamental way of analyzing composting systems. The first law of thermodynamics, for any system maintained at constant volume (isovolumetric) is generally presented as follows (Haug, 1993):

$$q_V = \Delta E \tag{2.3}$$

where,

q_V = heat flow in the system maintained at constant volume
ΔE = change in internal energy of the system

The heat per unit mass flowing into a substance (dq) can be defined as:

$$dq = mcdT \tag{2.4}$$

where,

c = the specific heat capacity

m = the mass

dT = the temperature change

Integrating equation (2.4), $q = m\int_{T_1}^{T_2} cdT$

Assuming a constant-volume process with constant specific heat, integration gives

$$q_V = mc\Delta T \qquad (\Delta T \text{ is not large}) \tag{2.5}$$

Hallström, Skjöldebrand, and Trägårdh (1988) defined specific heat or specific heat capacity as the amount of heat, h, necessary to raise the temperature of 1 kg of the material by 1°C or 1 °K, when there is no change in mass. The unit of c is therefore J/kg °K. If 0 °C is defined as the reference temperature,

$$h = \int_0^T cdT \tag{2.6}$$

Normally c is almost constant within the temperature region of interest and therefore the equation may be approximated to $h = cT$, with T in °C. The specific heat capacities for waste depend very much on the composition. The specific heat capacity of water is 4.18 kJ/kg °K while that of the solid constiuents is much lower, 1-2 kJ/kg °K. The specific heat capacities of a mixture of wastes may be estimated based on the composition as follows:

$$c = \sum m_i c_i \tag{2.7}$$

where m_i is the mass concentration, i.e. the proportion of each consituent (i) by mass. As a major fraction of the composting mass of this study was food waste, the thermal properties of some food constituents, as shown in Table 2.2, could be used. An approximate expression for specific heat of waste containing mainly water can be written as:

$$c = 4.18c_w \tag{2.8}$$

or

$$c = 4.18c_w + 2c_d \tag{2.9}$$

c_d being the dry matter content of material $(c_d = 1 - c_w)$. For fish and meat with $c_w < 0.25$, and for fruit and vegetables with $c_w > 0.50$, the following formula is suggested:

$$c = 1.67 + 2.5c_w \tag{2.10}$$

Table 2.2 Thermal properties of some food constiuents

Component	Mass concentration (kg/kg)	Density (kg/m^3)	Specific heat (kJ/kg)	Thermal conductivity (W/mK)
Water	c_w	1000	4.182	0.60
Carbohydrate	c_c	1550	1.42	0.58
Protein	c_p	1380	1.55	0.20
Fat	c_f	930	1.67	0.18
Air	c_a	1.24	1.00	0.025
Ice	c_i	917	2.11	
Inorganic minerals	c_m	2400	0.84	

Note from Heat Transfer and Food Products (5), by Hallström et al., 1988, (NY, USA:Elsevier Science Publishing Co., Inc.)

2.3 Numerical Scheme

A mathematical model of any physical system is a prediction device, which represents the full-sized phenomenon at a small scale. The models are intended to reproduce physical, chemical and biological reactions. If the equations depicting the physical events are known in sufficient detail, they can be useful in developing the design criteria of the real system without great difficulty (Jindal, 1995.) Many mathematical models have been investigated to describe the composting process. Unfortunately, there have not been many studies and reports on heat flow in composting systems. Such study will be useful for the improvement and control of forced aeration in composting procedures.

Theoretically, heat is the energy exchange between temperature differences, generally, from higher to lower temperature. Heat transfer is a study of how fast the energy is exchanged as heat. Three equations that have been used to describe the various modes of heat transfer are conduction, convection, and radiation (Rolle, 2000)

Conduction heat transfer is the normal transfer of energy within solids. It may also occur in gases and liquids, if they are stagnant or move slowly. Materials that conduct heat well, or rapidly, are called conductors and have high values of thermal conductivity. The mathematical equation for conduction heat transfer is Fourier's Law of Conduction (Rolle, 2000):

$$q = -kA\frac{\partial T}{\partial x} \tag{2.11}$$

where q is the heat transfer in the X direction crossing the normal area A due to the temperature gradient $\frac{\partial T}{\partial x}$ (Rolle, 2000).

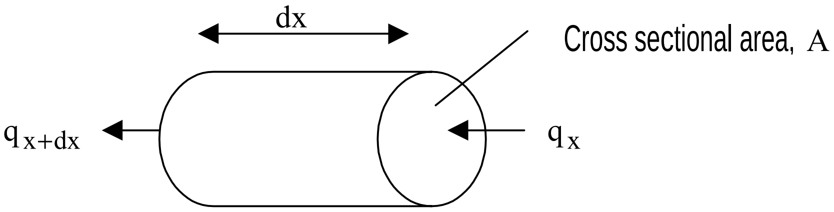
Convection heat transfer is the mode of energy exchange that is associated with heat crossing a boundary or surface between a solid and a fluid. It is a macroscopic phenomenon and, when considered in detail, the model does not satisfy the thermodynamic definition of heat transfer. It is a model that is used with the idea of a boundary layer of a fluid at a solid surface so that there can be heat flow to (or from) the bulk fluid around the solid. The mathematical equation for convection heat transfer is expressed by Newton's Law of cooling as shown below:

$$q = hA(T_s - T_\infty) = hA\Delta T \tag{2.12}$$

where T_s is the surface temperature, T_∞ is the ambient fluid temperature, and h is the convection heat transfer coefficient (Rolle, 2000).

The third model describing heat transfer between systems is radiation. This model is used for explaining observations of energy traveling through a distance without seeming to involve the intermediate volume (Rolle, 2000).

Consider a small element of material in a solid body as shown in the following figure:



The energy balance equation can be stated as follows (Rao, 1999):

$$\begin{gathered}\text{heat inflow during time } dt \\ + \text{ heat generated by internal sources during time } dt \\ = \\ \text{heat outflow during time } dt \\ + \text{ change in internal energy during time } dt\end{gathered} \tag{2.13}$$

With the rate expressions, equation (2.13) can be written as

$$q_x dt + \overset{\circ}{q}\, dxdt = q_{x+dx} dt + \rho c dT dx \tag{2.14}$$

where

$q_x = -kA\dfrac{\partial T}{\partial x}$ = the rate at which heat enters the face located at x

$q_{x+dx} = -kA\dfrac{\partial T}{\partial x} - \dfrac{\partial}{\partial x}\left(kA\dfrac{\partial T}{\partial x}\right)dx$

= heat outflow rate from the face located at $x + dx$

$\dot{q}$ = the rate of heat generation per unit volume (by heat source), W/m^3 or J/s/m^3

k = thermal conductivity of the medium, W/m/^{o}C

A = the area of cross section through which heat flows

$\dfrac{\partial T}{\partial x}$ = the rate of change of temperature, T with respect to the axial direction, x

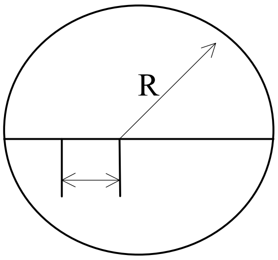
Dividing each term by dx, we obtain

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \overset{\circ}{q} = \rho c\frac{\partial T}{\partial t} \tag{2.15}$$

If a constant $\alpha = \dfrac{k}{c\rho}$, then

$$\frac{\partial^2 T}{\partial x^2} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2.16}$$

If cylindrical coordinate system is used instead of the Cartesian system and $\frac{\partial^2 T}{\partial x^2} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$, then equation (2.16) becomes



$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2.17}$$

where,

T = temperature, °C

r = distance along radial direction, m

α = thermal diffusitivity constant, m^2/s

ρ = bulk density = the mass per unit bulk volume, kg/m^3

t = time

Heat transfer is used for explaining and predicting many physical processes. The subject can be rationally approached if we reflect on the types of problems and solution to be encountered. In heat transfer, there are essentially two classes of problems (Rolle, 2000).

1) Given a temperature distribution, determine the heat transfer.
2) Given a rate of heat transfer, determine the expected temperature distribution.

Numerical schemes commonly used to solve the heat equation include the finite-difference method, the finite-element method, and the boundary-element method. Finite-different method is commonly used to solve unsteady one-dimensional heat transfer equations. It was the first numerical method to be used extensively for heat conduction. This method remains popular, not because it is superior to other methods for heat conduction, but because it is easier to implement and is also the most useful numerical scheme for heat convection problems (Mills, 1999).

The finite-difference solution for differential equations in mathematical-physics is carried out in two stages:

a) the writing of the finite-difference scheme (a difference approximation to the differential equation on a grid).

b) the computer solution for difference equations, which is written in the form of a high-order system of linear or non-linear algebraic equations.

The essence of the method of finite difference is as follows:

a) The continuous domain is replaced by a discrete set of points, called grid.
b) Instead of a function of continuous arguments, a function of discrete argument is considered. The value of this function is defined at the nodes of the grid or at other elements of the grid and is called the grid function.
c) The derivatives entering into the differential equations and the boundary conditions are approximated by the difference expression, thus the differential problem is transformed into a system of linear or non-linear algebraic equations. Such a system is often called the finite-difference scheme (Shashkov, 1996).

2.4 Previous Studies

2.4.1 General

Aeration rate and temperature profiles are the principal variables to be monitored during the composting process, with air supplied by agitation, forced aeration, or combination of both. The disadvantage of agitation or windrow composting is that the temperature of the mass is never properly controlled, leaving unavailability in allowance of optimum temperature condition for biodegradation. Whereas, static pile composting has major disadvantage in the inability to readily change the physical conditions within the pile mass. A very typical problem is the occurrence of excessive drying which influences process inhibition due to dryness. The combination of agitation and forced aeration absolutely overcomed both problems but that it also causes an increase in capital investment. Admittedly, there are alternatives for controlling aerobic composting, though, reactor based systems seemed to be adequate for all small-scale studies.

Leton and Stentiford (1990) studied the relationships between composting parameters related to aeration rates provided to a static composting pile. They had reached a conclusion that only the automated aeration system could actually cater for the dynamic nature of the composting process. Advantages such as a means of monitoring aeration effectiveness, and an indication of the end of active composting could be incorporated into the system. The forced aeration method of static pile composting was claimed to enhance the process, and the active decomposition period could be cut down from 40 days or more in the windrow system to about 21 days in the static pile system. This reduction in active composting time (the period from the time the pile is built to when it is taken off the aeration pad) was not solely a feature of the aeration method but depended on a number of other interactive factors. These factors were: nature of raw material, mixing ratio (C/N ratio), moisture content, particle size, and temperature within the compost mass. Serveral programs were designed for an automation of aeration rates. An automated rate of aeration control was determined from the feedback of information on oxygen and/or temperature levels in the pile.

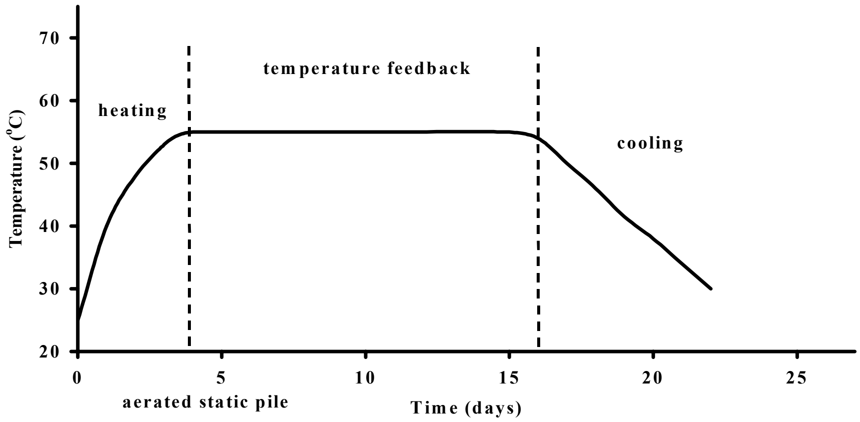
In another study (Stentiford, 1996), in order to develop a mathematical model for relationship between heat generation and temperature distribution of a composting system, forced aeration was utilized as a control variable. Air was supplied to the composting mass by a pressurized system, typically low head (below 150 mm) high volume fan units. Three possible methods were employed:

(a) blowing air into mass, positive pressure
(b) sucking air through the mass, negative pressure
(c) hybrid (combination of both), this method could give greater flexibility in operation.

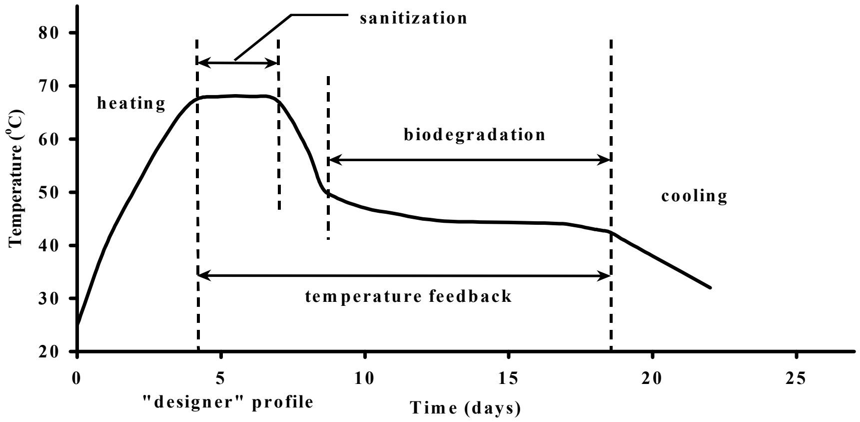
The forced aeration was controlled to distribute the air throughout the mass. The positive pressure seemed to be the best methodology because, it was easy to provide and properly control the aeration rate. Although, the reactor-based systems were rather large but small bench-scale and pilot-scale were often utilized for research.

2.4.2 Heat and Temperature Distribution Related Studies

Figure 2.1 shows the typical temperature/time profiles for different composting systems. This figure shows that the temperature will rapidly increase for the first composting stage and reach the optimum temperature within 7 days. Then sanitisation occurs during the optimum temperature period. As the temperature decreases, the biodegradation takes place for certain period of time and finally cooling stage.



aerated static pile



"designer" profile

Figure 2.1 Typical Temperature/time profiles for different compost systems [Note from Composting Control, Principles and Practice, The Science of Composting.(54) by Stentiford E.I., 1996]

MacGregor, et al. (1981) summarized heat output-temperature interaction as follows: soon after organic material is assembled into a self-insulating mass, the temperature starts to increase as metabolic heat accumulates. At first, mesophilic growth is stimulated by higher temperatures, but, as inhibitive levels are reached, this leads to a self-limiting condition. Because the elevated temperature now induces thermophilic growth, the pattern is repeated in a second, hotter stage. At peak thermophilic temperatures, the metabolic activity is relatively slight. In sum, the system is prone to self-limit via the excessive accumulation of heat. The study utilized the above relationships in a field-scale process of static-pile conmposting, utilizing a mixture of sewage sludge and wood chips. Heat removal was matched to heat output through a temperature feedback control system, using heat balance method, thereby maintaining biologically favorable temperatures. As a result, the important mechanisms of heat removal were vaporization and dry air convection, both of which were dependent on ventilation. Other mechanisms associated with heat exchange at surfaces (radiation, conduction) were negligible in the large, well-insulated system. Air entered the pile at 25 °C and the mass of water vapor/mass of dry air (ω) was 0.012. The heat content or enthalpy (h) was 74 kJ per kg of dry air. With passage through the pile, the air had an increase in temperature and became saturated, exiting at 50 °C. The heat removed from the pile was 221 kJ per kg of dry air. The component of removal caused solely by the temperature increase of dry air equals the specific heat of air (1.0 kJ/kg °C) times the increment in air temperature (25 °C), giving 25 kJ per kg of dry air or 11 % of the total removal, and 89 % of the heat was removed through vaporization. Thus, in the temperature range of interest, approximately $^{9}/_{10}$ of the heat was removed through vaporization.

Devkota (1984) stated that a compost pile could generate significant amount of heat from decomposition of organica materials such as agricultural residue, e.g. the litter of straw, grass etc. Decomposition could be accelerated by addition of water, or *Azospirillum* (nitrogen fixing bacteria). Heat generation greatly varied with the hight of compost pile and the time it took to decompose.

Sikora and Sowers (1985) investigated the effect of temperature control on the composting process by monitoring two laboratory-scale self-heating composters. The cylinder holding the composting mixture was made small (10 cm-radius) to allow controlling of the temperature by aeration. Raw waste mixed with wood chips was composted. The inner cylinder was then placed in the outer cylinder, which was sealed airtight. The thermister and thermocouple were inserted, aeration was controlled at either preset flow rates or according to the demand necessary to hold the temperature. Identical composters were set up using the same mixture with different aeration. The aeration rates were 900-1800 m^3/hr-Mg (oven-dry basis). Continuous temperature recording were used to monitor the composting runs. The peak temperatures recorded were approximately 60 °C and above. When temperatures declined from their peak to near ambeint level and remained there for 2-3 days, the run was terminated. The temperature decline was an indication of a completed composting cycle. The results showed that aeration significantly affects the duration of the composting cycle and the extent of decomposition.

Nakasaki, et al. (1985) investigated the effect of temperature on sewage sludge composting. They conducted experiments at three different temperatures, 50, 60, and 70 °C. The results showed that the energy yielded from catabolism (a part of metabolism, in which the complex compound dissosiates and release energy; thus giving energy from substrate within the body, i.e., breathing, digesting) is rather uncoupled with the anabolism (a part of metabolism, which forms complex compounds from the simpler ones, including absorption and energy preserved within the body) at 70 °C in the metabolism of indigenous organisms in the composting process. The respiratory quoteint, RQ, is defined as $\frac{\text{volume of } O_2 \text{ observed/h}}{\text{volume of } CO_2 \text{ observed/h}}$ and is equal to 1. Higher respiratory quotient was observed at 70 °C than at any other temperature.

Lindratsirikul (1988) conducted experiments on composting of water hyacinth by aerobic process. The peak tempertaures were recorded to be between 45-60 °C within 7-15 days in the static piles with aeration rate ranging 0.3-1.54 m^3/day/kg of volatile solids. The temperature increase observed was to be faster for the non-aerated composting pile than those with aeration. The maximum temperature of 59.8 °C was achieved in less than 15 days with 0.3 m^3/day/kg of VS aeration rate. Ventilation by aeration through the piles could be a major factor in the temperature variation.

Many studies of oxygen uptake rate have been conducted using batch reactors and have shown an increase in oxygen uptake rate with increasing temperature. According to Haug, (1993), the rate of oxygen consumption may continue to increase with temperatures up to 68 °C, however it would be expected to decrease at higher temperatures. In any composting system, the aeration system must be capable of meeting the maximum oxygen consumption rate demanded by the microbial population. Higher aeration rates would be required to remove the heat released from consumption of oxygen. Moreover, if reheating is not enough, it causes regrowth of organisms and then odor is initiated. Odor control depends on stabilization in terms of energy available for biological metabolism. The energy required varies with temperature. Therefore, the relationship between energy produced (heat) and temperature has been studied to efficiently accomplish biological degradation of composting processes (Shaw and Stentiford, 1996).

Miller (1996) suggested that the heat generated is proportional to the metabolic activity and is a fundamental means of observing the role of composting microbial population in situ. In turn, heat monitoring is the basis of temperature control in engineering design and management of composting systems. Moreover, the prediction of heat evolution rate relates to the substrate to be composted and processing conditions, and can serve as aeration basis of the systems design. In another study, heat evolution during composting of sewage sludge was investigated. A physical model system was developed to permit measurement of heat evolved during the composting of sewage sludge, and to remove heat through ventilation and conduction in a manner realistically comparable to field scale systems. Heat evolutions of approximately 15,000 to 22,000 J/g organic material decomposed were observed with the peak outputs of almost 700 J/g of initial sludge volatile per 12 h period. Composting activity appeared to be enhanced by ventilation, independent of temperature or high interstial oxygen concentration, but possibly related to particle surface turbulance (wind) factors improving oxygen transfer.

Stentiford (1996) also reported that temperature determines the rate at which biological processes take place. The maximum temperature in the composting pile is intended for:

(a) sanitisation, for which high temperature is the most effective, and

(b) stabilization, for which high temperature inhibits the biological process.

The compromise position ascribed optimum temperatures as follows:

> 55 °C	maximizes sanitisation
45-55 °C	maximizes biodegradation rate
35-40 °C	maximizes microbial diversity (variety)

The heat carrying capacity of the air used in aerobic system is not responsible for removing the excess heat from the system but it does so indirectly by evaporating moisture from the composting mass.

Blanc, et al. (1996) indicated that temperature increase involves a rapid transition from a mesophilic to a thermophilic stage (65-75 °C) within a few hours, provided the pile is regularly aerated. This study was entirely focused on the relationships between varieties of microorganisms and thermophilic stages.

Prajaubwan (2000) investigated the respiration heat of fresh food products by direct and indirect methods. Direct method involved the measurement of temperature distribution of okra samples contained in the insulated boxes with aeration. The heat of respiration was determined based on Fourier equation for heat conduction. In the indirect method, heat of respiration was calculated from CO_2 produced by the product. The results showed that airflow rate did not have any significant effect on the heat of respiration. It was also found that the heat of respiration of okra increased when the sample size was reduced but not so significantly.

In another study, the empirical model and kinetic behavior of thermophilic composting of vegetable waste were investigated in a subtropical area (Taiwan) (Haung, et al., 2000). The temperatures of about 50 ^{o}C ± 2^{o}C were controlled for a laboratory-scale process to generate the experimental data of thermophilic composting of vegetable waste. The obtained empirical model appeared to be a quadratic form and could also be used to predict operating conditions, i.e., weight basis ratio of the organic material, aeration rate, reaction temperature, and time for thermophilic composting of vegetable waste. The biochemical reaction of thermophilic composting of vegetable waste followed Monod-type kinetics with the specific substrate utilization rate constant obtained for this study.

A study of the effect of microaerobic conditions on autothermal thermophilic aerobic digestion process was conducted by Mavinic, et al. (2001). A pilot-scale, first-stage, autothermal thermophilic aerobic digestion reactor (with a volume of 72 L), provided with the aeration rate of 0-100 ml/min, was used for this study. The results showed that the temperature in the reactor did not vary significantly in each test. There were minor variations, which were probably due to changes in ambient temperature and imperfect insulation. The temperature profiles had a sawtooth pattern, reflecting the feed and waste cycles. The average temperatures during the experiments were 55.6, 54.9, 48.2, 51.0 and 49.9 ^{o}C, for airflow rates of 0, 25, 50, 75, and 100 ml/min, respectively. However, the results of their study seemed to indicate that small amounts of air supply and microaerophilic conditions maybe beneficial to composting process.

Chapter III

Research Methodology

3.1 Research Procedure

The overall procedure involved, collection of the waste materials, obtaining the appropriate mixture for the aerobic process, and recording the temperatures of the composting mass as the biodegradation took place. Figure 3.1 shows the overview of the complete procedure.

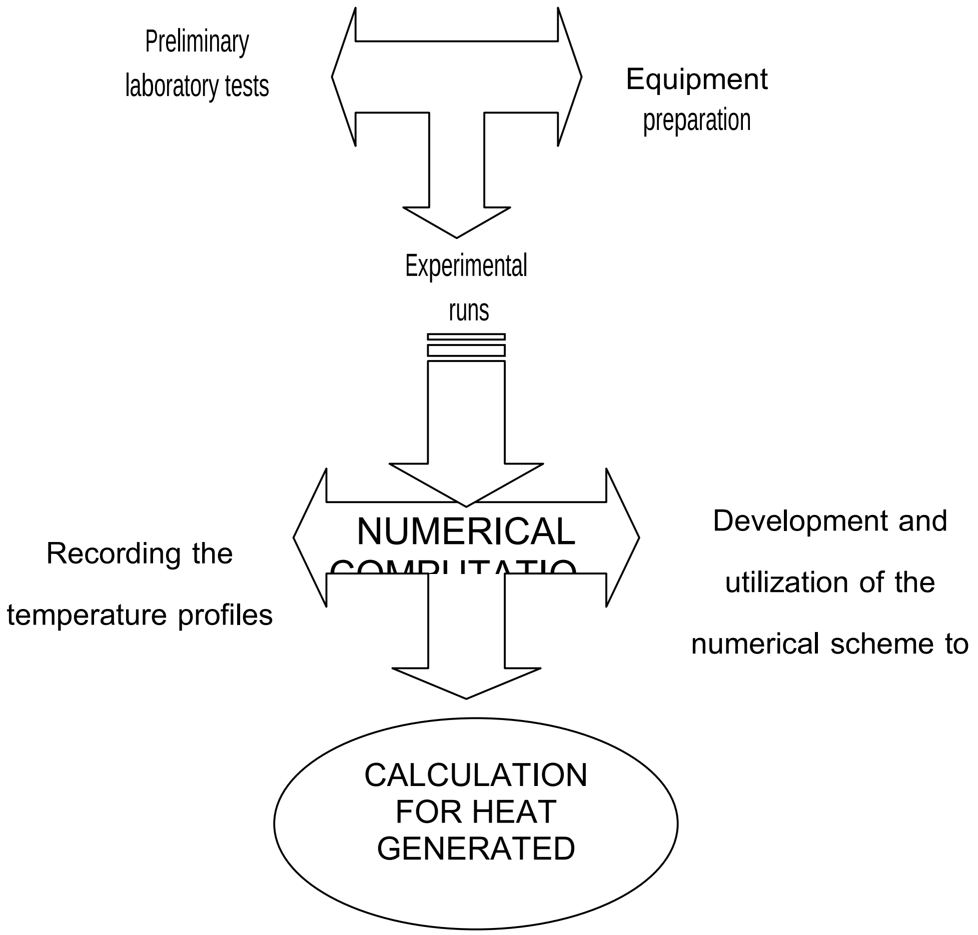
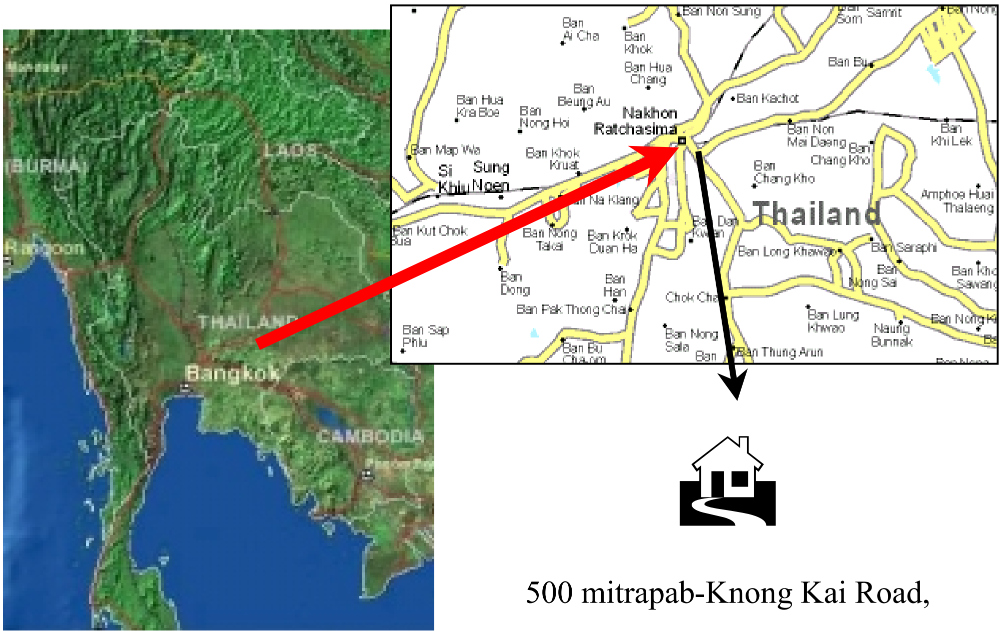


Figure 3.1 Schematic diagram of research procedure

3.2 Experimental Location

Experimental site of this study was at a house (Suntudtong residence) located at kilometer 7 on Mittrapab-Knong Kai road, Nakhon Ratchasima, which is in the Northeastern region of Thailand. Figure 3.2 shows the experimental location.



500 mitrapab-Knong Kai Road,
Ampher Maung, Nakhon Ratchasima

Figure 3.2 Experimental location (Note from Nakhon Ratchasima, Thailand Map & Placename Index (2002) [on-line] and National Geographic. (2002). **Atlas of the World**. [on-line].)

3.3 Experimental Setup

a) Composters: Four cylindrical composters made of zinc sheet, insulated with microfiber, with dimensions: length (l) of 1.0 m, diameter (d) of 0.5 m, and volume ($\forall$) of approximately 0.196 m^3, were used for the pilot-scale experiments of this study as shown in Figure 3.3.

b) Thermocouples: Type K thermocouples were inserted at different positions in each reactor for temperature measurement, as shown in Figures 3.4 and 3.5.

c) Air diffusers: $\frac{1}{2}''$ PVC pipes with $\frac{1}{8}''$ holes in all directions were inserted in the center of each composter, as shown in Figure 3.6.

d) Aeration: An air compressor was used to supply air to all composter as shown in Figure 3.7.

e) Air flow meter: A flow meter was installed to monitor aeration rate provided to the composters, as shown in Figure 3.8.

f) Data loggers: Data loggers and a computer were used to monitor time and temperatures (Figure 3.9).

Figure 3.3 Cylindrical Composters

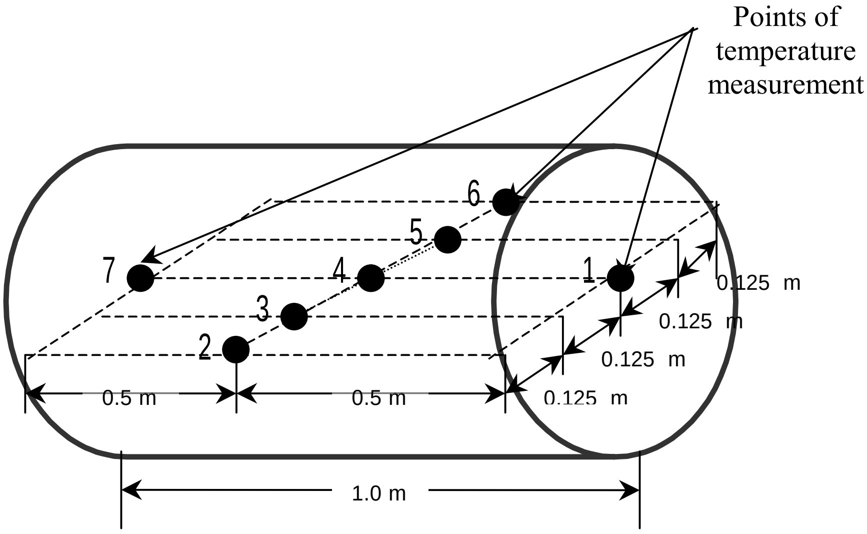


Figure 3.4 Points of temperature measurements

Figure 3.5 Temperature measurement points inside the composters

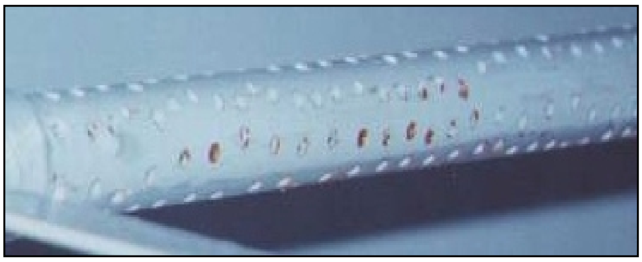


Figure 3.6 PVC pipe as air diffuser

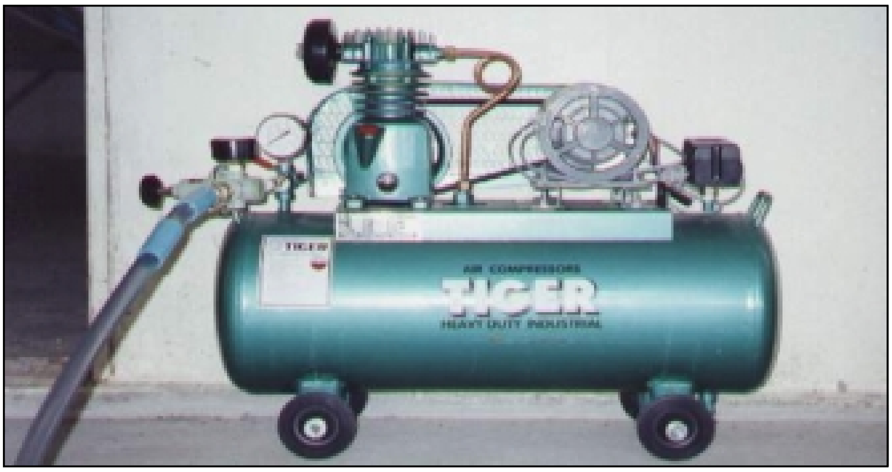


Figure 3.7 Air compressor

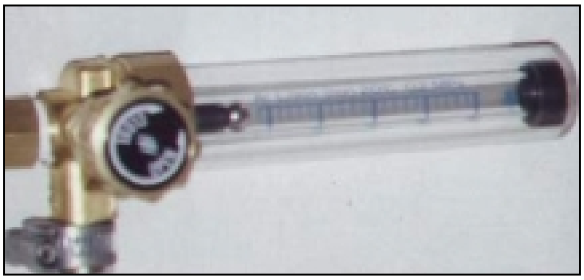


Figure 3.8 Air flow meter

Figure 3.9 Data loggers and a computer

3.4 Composting Materials

Mixture of two different organic waste materials was used to conduct the composting experiments for this study. The organic waste components were yard waste and food waste. Yard waste consisted of grass trimmings and fallen leaves as shown in Figure 3.10. Food waste consisted of household kitchen waste mixed with vegetable and fruit trimmings, as shown in Figure 3.11. Sources of the waste materials for the experiments are briefly described as follows:

a) Grass trimming and fallen leaves were collected from Suntudtong Farm on Mittrapab-Paktongchai road, in front of the Suranaree University of Technology main entrance.
b) Food waste was be collected from Korat City neighborhood household trash bins mixed with Sura Nakhon market (Nakhon Ratchasima) vegetable and fruit trimming waste.

3.5 Preparation of Composting Mixture

Waste samples of all fractions were analyzed in the laboratory for the determinations of: bulk density, moisture content, total solids (TS), total volatile solids (TVS), organic carbon, total organic nitrogen, and C/N ratio. The composting material mixture ratio was calculated from the preliminary laboratory analyses (Appendix C). The aeration requirements were estimated following the examples of some previous studies as shown in Appendix D.

The waste samples were chopped and cut as recommended by Tchobanoglous, et al., 1993; for optimum results, the size of solid waste should be between 25 and 27 mm (1 and 3 in.). Figure 3.12 shows food waste and yard waste mixture (weight basis ratio), before being placed in the composters for each composting run.

3.6 Composting Runs

Four experimental runs, RUN I, II, III, and IV, were conducted with different aeration rates provided for each composting process. Table 3.1 shows the experimental plan of this study. Time and temperature were recorded hourly (Figure 3.13). Experimental results were analyzed with the developed numerical scheme.

(a) Household yard waste

(b) Yard waste before chopping

Figure 3.10 Yard waste collected for the experiment

(a) Food waste from restaurants

(b) Fresh food market dumping site

Figure 3.11 Food waste collected for the experiment

Table 3.1 Duration and airflow rates of four composting runs

Experimental run	Aeration rate Q_{air}	Number of days run
RUN I	1.25 L/min (1.8 m^3/day)	85 days
RUN II	2.50 L/min (3.6 m^3/day)	65 days
RUN III	3.75 L/min (5.4 m^3/day)	85 days
RUN IV	7.50 L/min (10 m^3/day)	49 days

Figure 3.12 Wastes mixing

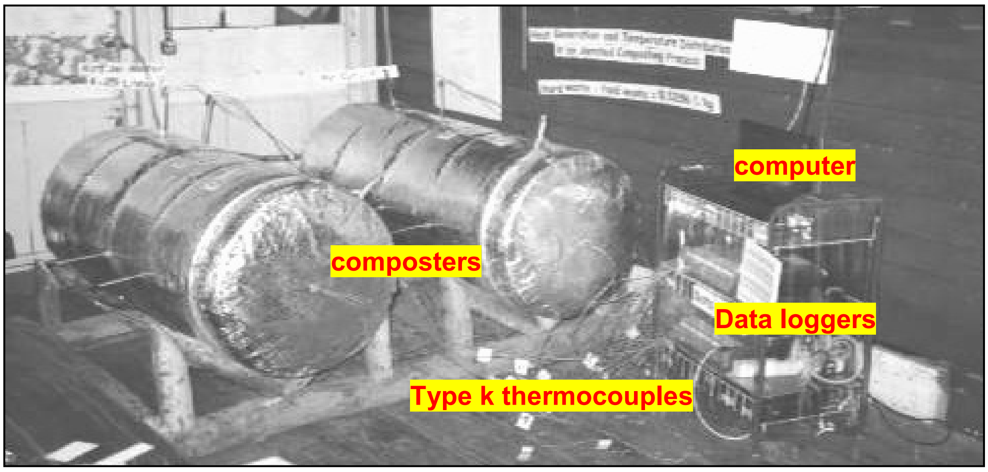


Figure 3.13 Data loggers for the recording of temperature profiles

3.7 Thermal Properties of Composting Materials

Thermal conductivity (k): The thermal conductivity, k, of solids and liquids is considered to be constant and usually expressed in units of cal/(h-cm^2-^{o}C/cm) or Btu/(h-ft^2-^{o}F/ft). Theoretically, heat conducts from the center of heat source through the media. If the media (composting material) has poor thermal conductivity, the temperature rises faster at the center of heat source. Values of k between 2 and 4 cal/(h-cm^2-^{o}C/cm) have been measured for different compost materials (Haug, 1993). The basic equation used for calculation of thermal conductivity (Prajaubwan, 2000) is given as below:

$$T = \frac{q}{4\pi k} \ln t \qquad (3.1)$$

Where,

T = temperature

q = heat applied to the heat source

t = time

k = thermal conductivity

Thermal conductivity measurement involves a heat source (thermal conductivity probe) provided with a known constant current and voltage. The temperature and time are measured and recorded by type T thermocouples and the data logger, respectively. Thermal conductivity (k) may be determined from the slope (m) of the straight line resulting from the semi-logarithmic plot of time (t) versus temperature (T). Figure 3.14 shows the schematic layout of the thermal conductivity measurement set up used in a laboratory at the Asian Institute of Technology (AIT), in Pathumthani province of Thailand.

Power input to a heat source of length, L, may be expressed as follow:

$$P = \frac{IV}{L} \qquad (3.2)$$

where,

P = power supplied to the heat source, W/m

L = effective length of the heat source, m

I = current, amp and V = voltage, volts

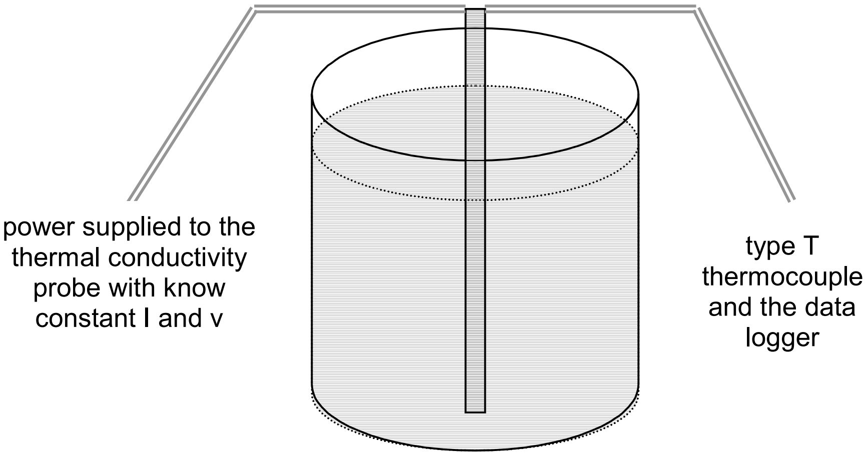


Figure 3.14 Schematic layout of the thermal conductivity measurement setup

and

$$q = \frac{IV}{4\pi kL} = \text{heat applied to the media}$$

Agar gel was used to calibrate this setup (Figure 3.15). Four samples of composted materials of different time-durations, and so, having different moisture contents, were used to obtain average thermal conductivity of the composting end product (Figure 3.16).

Thermal diffusivity (α): Thermal diffusivity could be calculated from the relationship, $\alpha = \frac{k}{\rho c}$. The thermal conductivity (k) was obtained from the above experiment, specific heat capacity (c) of the compost material was taken from some previous study and density (ρ) of the compost material mixture was measured in the laboratory.

Heat generation ($\overset{\circ}{q}$): A computer program was used to create the simulated temperature profiles for each experimental runs' conditions, i.e., initial temperature, ambient temperature, etc. Heat generated for each time-period was assumed in the program. The temperature outputs of the simulated profiles were compared with the experimental profiles to obtain heat generated, $\overset{\circ}{q}$.

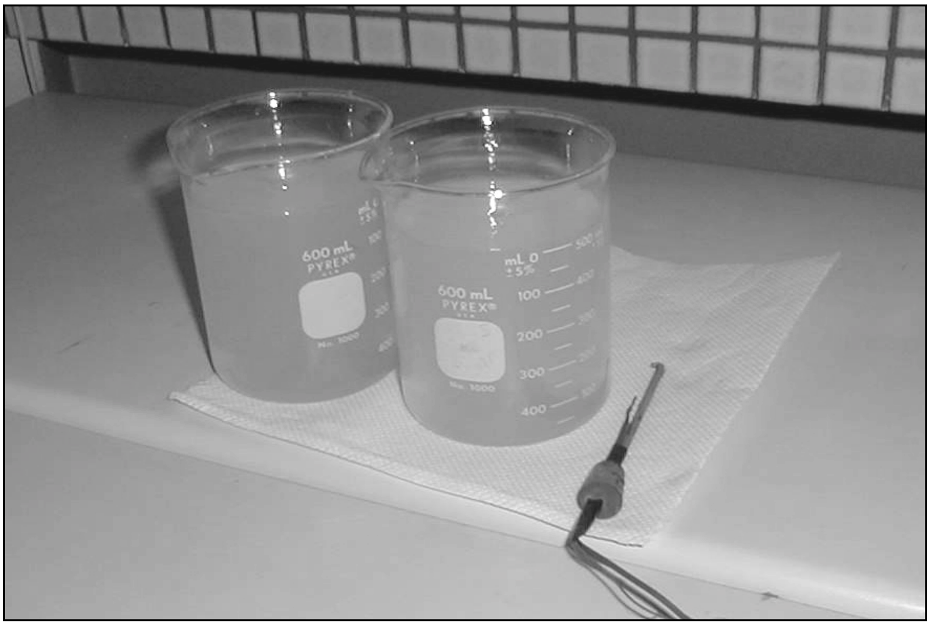


Figure 3.15 Agar gel and the thermal conductivity probe

Figure 3.16 Thermal conductivity measurement at AIT

Chapter IV

Results and Discussion

4.1 Characteristics of Raw Materials

The results of the laboratory analyses of the waste samples collected from the selected sources are shown in Table 4.1. Details are shown in appendix B.

Table 4.1 Raw Material Characteristics

Organic fraction	Food waste	Yard waste
% moisture	80.96 ± 0.29	50.54 ± 0.28
% solids	19.04 ± 0.29	49.46 ± 0.28
% VS	80.6 ± 1.93	80.57 ± 2.76
% ash	19.4 ± 1.93	19.43 ± 2.76
% C	39.22 ± 0.24	40.46 ± 0.72
% N	1.78 ± 0.02	1.25 ± 0.04
C/N ratio	22.04 ± 0.23	32.44 ± 0.52
Bulk density	0.74 kg/L	0.075 kg/L

4.2 Composting Materials Mixture and Aeration Rates

The preliminary laboratory analyses results were used to calculate organic wastes' mixture ratio to fulfill the requirement for C/N = 30. The obtained ratio of food waste: yard waste was found to be 1: 0.0286 kg. The volume of each composter was 0.196 m^3. Hence, the amount of organic waste material fractions to be mixed were 114 kg and 3.5 kg for food waste and yard waste, respectively, as shown in appendix C. The aeration rate required for the stoichiometric process (Chapter II, equation 2.1 and 2.2) was found to be 0.105 L/min (0.016 m^3/d) (shown in appendix D). Due to the limited capacity of the equipment used for airflow rate measurement, the aeration rates (Q_{air}) for four runs were selected as 1.25 L/min (1.8 m^3/d), 2.5 L/min (3.6 m^3/d), 3.75 L/min (5.4 m^3/d), and 7.5 L/min (10 m^3/d) for RUN I, II, III and IV, respectively. Table 4.2 shows the conditions of four experimental runs conducted in this study. Each run was completed when the temperature had read stale state.

Table 4.2 Experimental conditions of four runs

Run	Q_{air}	Duration	Number of days
I	1.25 L/min (1.8 m^3/d)	Aug 19th – Nov 11th 2001	85
II	2.50 L/min (3.6 m^3/d)	Feb 18th – Apr 23rd 2001	65
III	3.75 L/min (5.4 m^3/d)	Aug 19th – Nov 11th 2001	85
IV	7.50 L/min (10 m^3/d)	Mar 8th – Apr 26th 2001	49

4.3 Composting Runs

It was realized that the characteristics of organic waste varied initially. Although, yard waste did not show significant variation but food waste did. Therefore, synthetic food waste was prepared for each run to keep the initial characteristics steady, as shown in Table 4.3. The constituents of synthetic food waste included: soggy bananas, cabbage trims, powder milk, left over rice, and food waste collected from the restaurants. Samples of composting mixture were analyzed before and at the end of each run. Characteristics of initial mixture and final products are shown in Table 4.4.

Figures 4.1-4 present the initial and final characteristics of compost material for the four runs. Table 4.5 shows the percent increase/decrease in the initial and final characteristics of the composting mixture of the four experimental runs. Figures 4.5-12 show the changes in the monitored characteristics of the composting mixture during the four runs. The characteristics of the final product did not clearly indicate that composting process had reached the maturity-state.

Table 4.3 Variation in the initial characteristics of the composting mixture

Initial sample mixture	% Moisture	% solids	% VS	% ash	% C	% N	C/N Ratio	pH
Run I	77.93	22.07	83.13	16.87	40.09	1.49	27.13	5.50
Run II	81.91	18.09	95.87	4.13	37.84	1.67	22.74	4.00
Run III	76.92	23.08	83.29	16.71	41.01	1.72	23.82	4.33
Run IV	75.29	24.71	86.50	13.50	40.27	1.49	27.11	5.00
Average	78.01	21.99	87.20	12.80	39.80	1.59	25.20	4.71
Standard deviation	2.82	2.82	5.98	5.98	1.37	0.12	2.26	0.67

Table 4.4 Initial and final characteristics of composting mixture for each experimental run

Sample	% Moisture	% Solids	% VS	% ash	% C	% N	C/N Ratio	pH
Run I-initial	77.93	22.07	83.13	16.87	40.09	1.49	27.13	5.50
Run I-final	72.74	27.26	50.86	49.14	32.53	3.10	10.50	7.82
Run II-initial	81.91	18.09	95.87	4.13	37.84	1.67	22.74	4.00
Run II-final	61.85	38.15	46.68	53.32	23.66	1.59	14.92	7.25
Run III-initial	76.92	23.08	83.29	16.71	41.01	1.72	23.82	4.33
Run III-final	72.47	27.53	60.14	39.86	36.44	2.89	12.61	7.62
Run IV-initial	75.29	24.71	86.50	13.50	40.27	1.49	27.11	5.00
Run IV-final	65.32	34.68	59.68	40.32	23.96	2.12	11.30	8.50

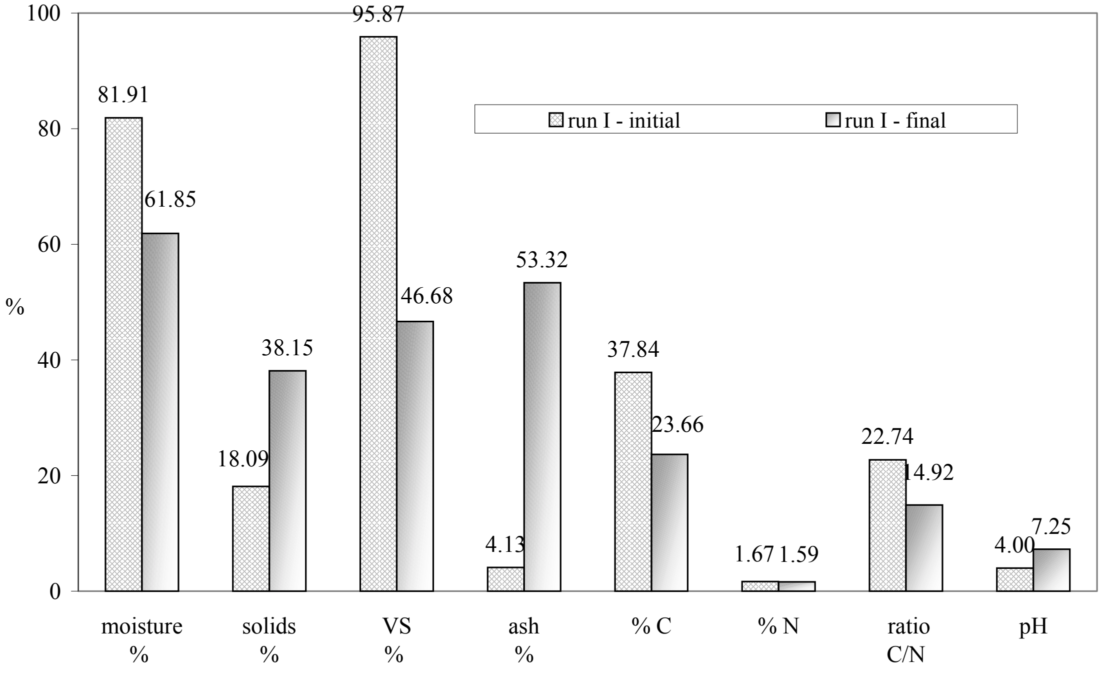


Figure 4.1 The compost material characteristics during RUN I

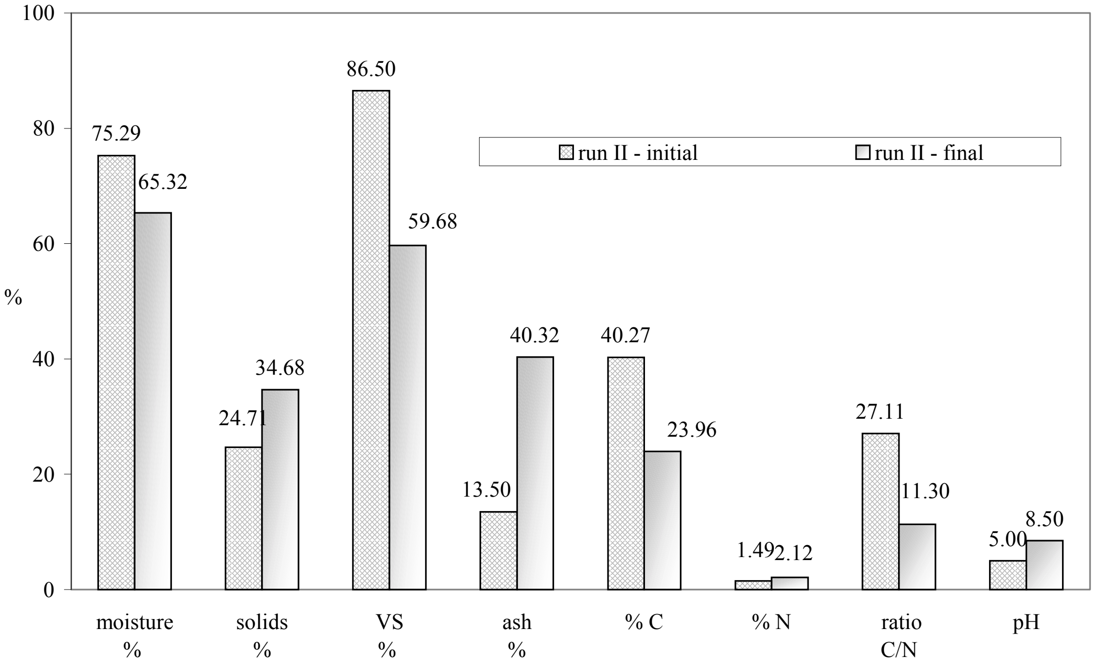


Figure 4.2 The compost material characteristics during RUN II

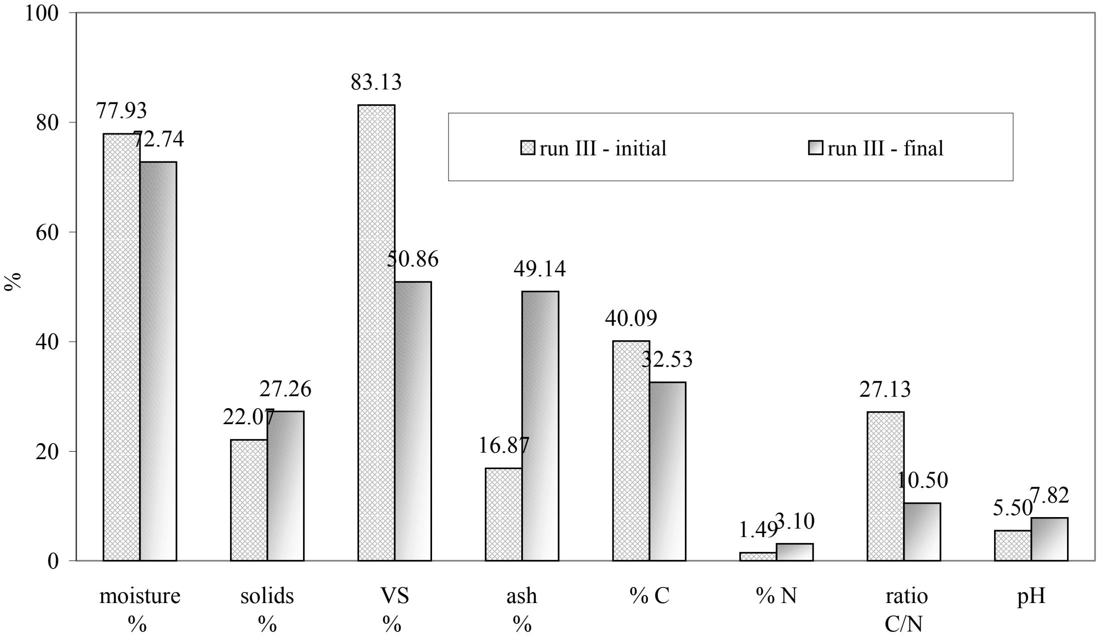


Figure 4.3 The compost material characteristics during RUN III

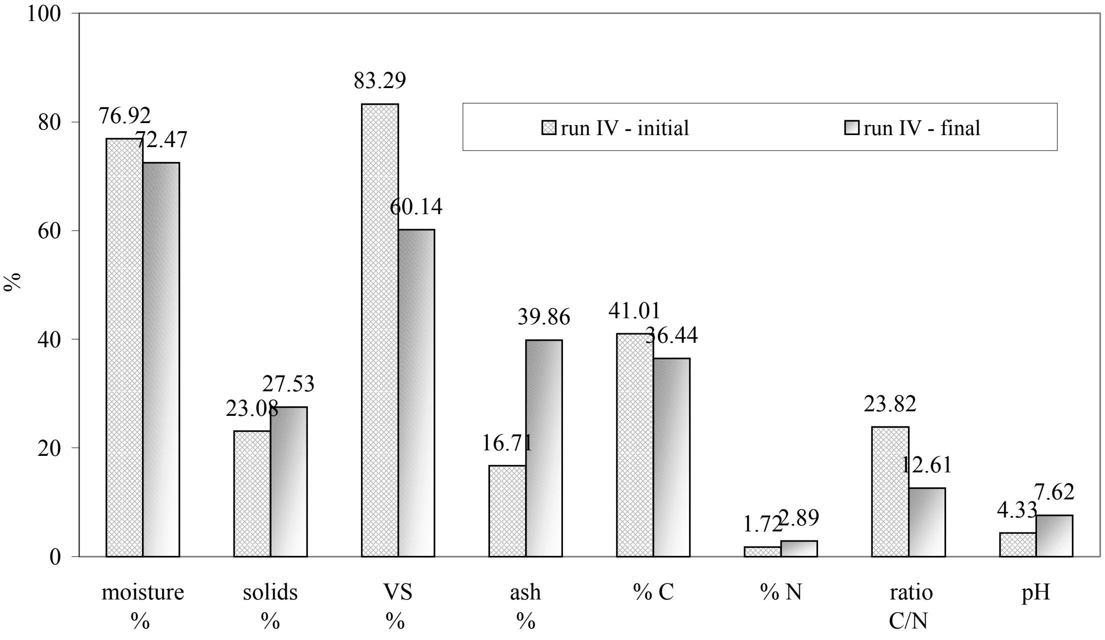


Figure 4.4 The compost material characteristics during RUN IV

Table 4.5 Percent decrease/increase in the characteristics of the compost material

Sample	% moisture	% VS	% C	% N
Run I	(20.06)	(49.19)	(14.17)	(0.08)
Run II	(9.97)	(26.82)	(16.31)	0.63
Run III	(5.19)	(32.27)	(7.56)	1.61
Run IV	(4.45)	(23.15)	(4.58)	1.17

Note (--) means decreasing

The organic waste biodegradation rate is based on various parameters including environment conditions, waste characteristics, and stage of composting process. It can be seen from the results in Table 4.5 that there were decreasing trends in moisture content, volatile solids (organic fraction), and organic carbon of the composted products as compared with the initial characteristics of the organic wastes mixtures. The decrease ranged from 4.4-20.1 %, 23.1-49.2 %, and 4.6-16.3 % for moisture content, volatile solids, and organic carbon, respectively. However, organic nitrogen content was slightly increasing in all but RUN II. Considering the end products, RUN II was the best run considering the end product; the highest organic carbon was decreased in this experimental setup.

The product's moisture content was rather high comparing to soil and other commercial solid fertilizers. This could be due to the fact that experimental setup was not designed to have aeration to the composting mass and the environment, leading to high moisture content in the composted mass. Thus, further drying was needed.

Effective composting requires appropriate nutrient sources, as they are 'food' for the microorganisms that drive the process. A sufficient level of volatile solids is required for rapid heating. Other organic nutrients requirement, principally carbon and nitrogen is expressed as a C/N ratio. The range 25:1 – 40:1 is considered to be suitable for the process. Moreover, sufficient oxygen must be supplied to allow the aerobic process to sustain.

A moisture content of between 40-60% is also recommended to be maintained during the process. At higher moisture levels, porosity is usually adversely affected and it becomes impossible to maintain oxygen levels. At lower moisture levels, biological activity is insufficient for sustaining the process.

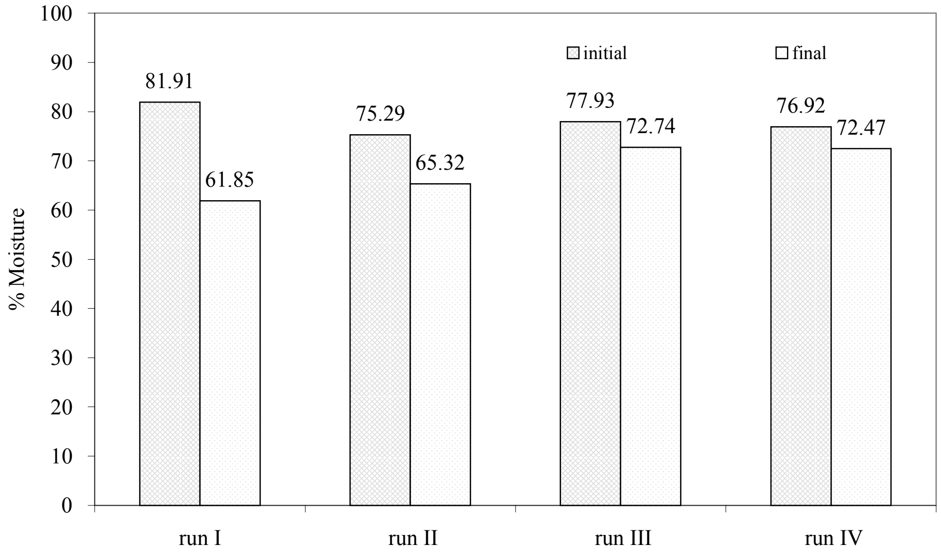


Figure 4.5 Changes in moisture content of the composting mixture during each run

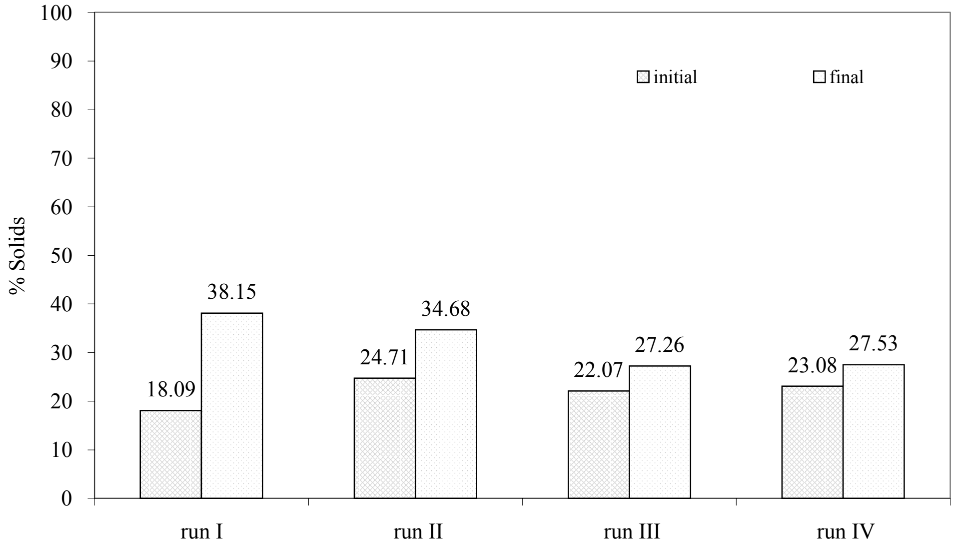


Figure 4.6 Changes in total solids (TS) of the composting mixture during each run

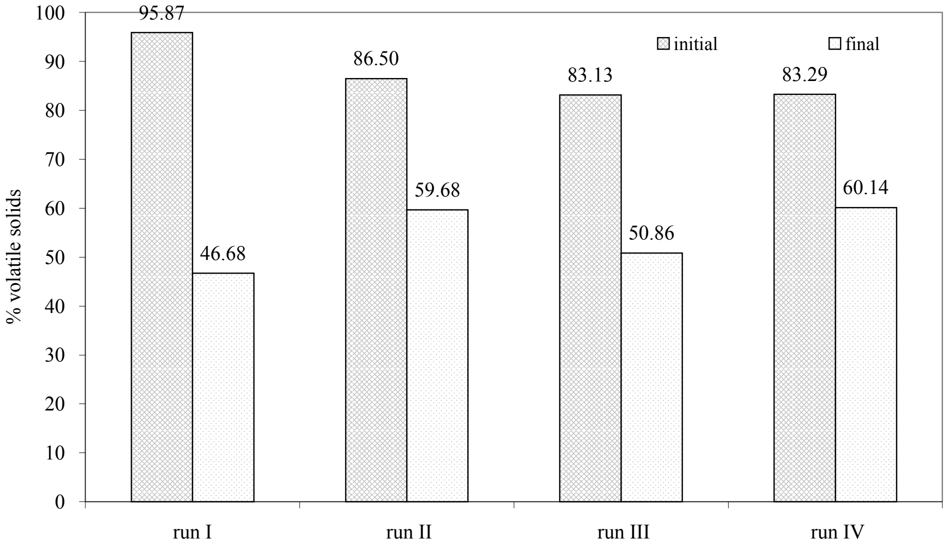


Figure 4.7 Changes in total volatile solids (TVS) of the composting mixture during each run

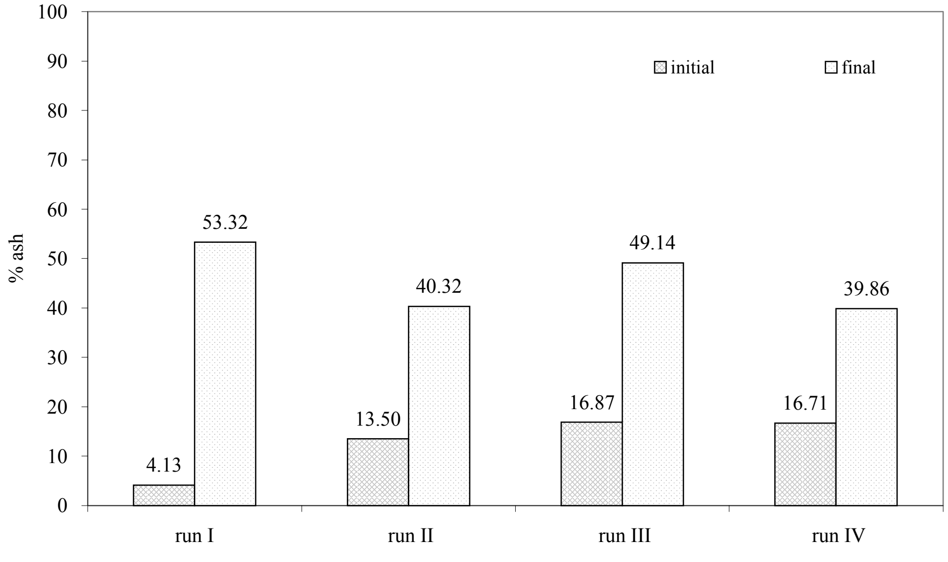


Figure 4.8 Changes in total ash of the composting mixture during each run

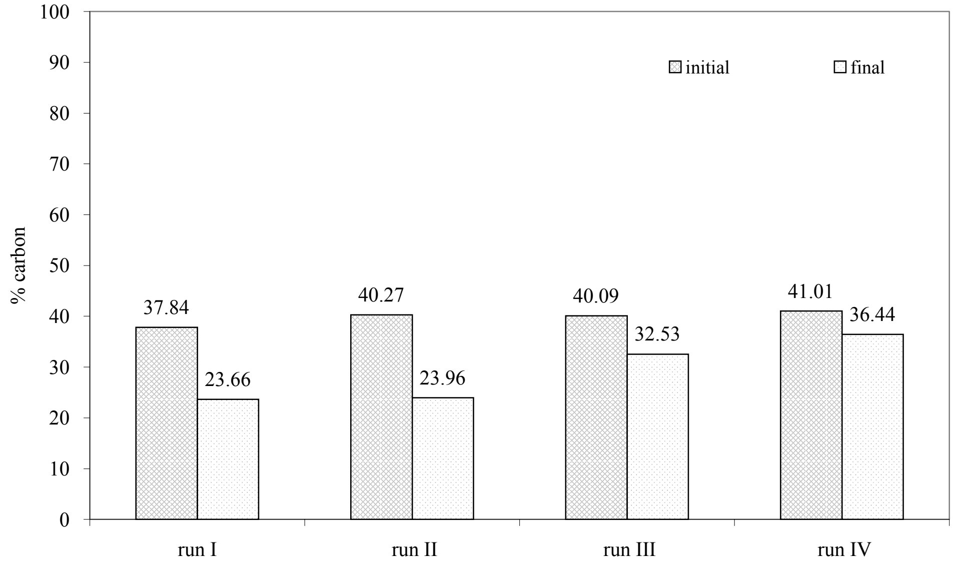


Figure 4.9 Changes in organic carbon (C) of the composting mixture during each run

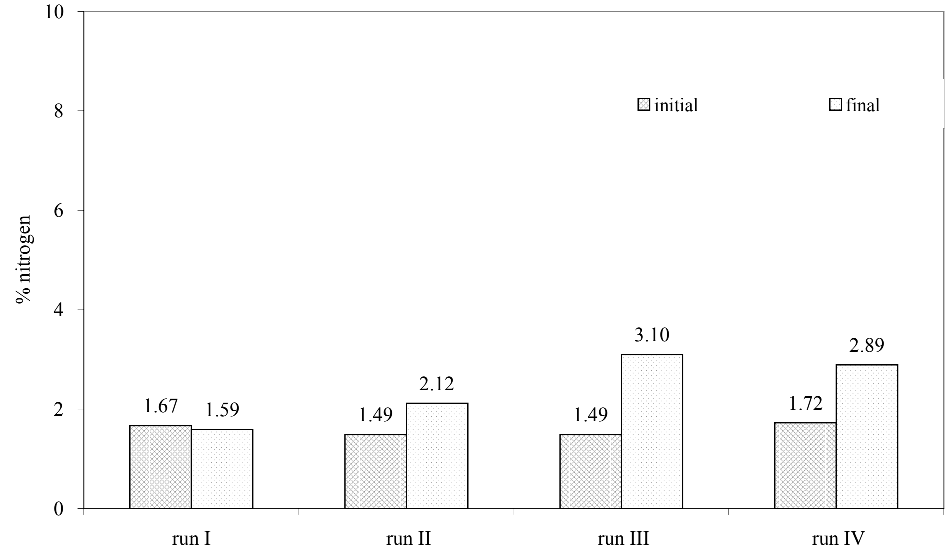


Figure 4.10 Changes in organic nitrogen (N) of the composting mixture during each run

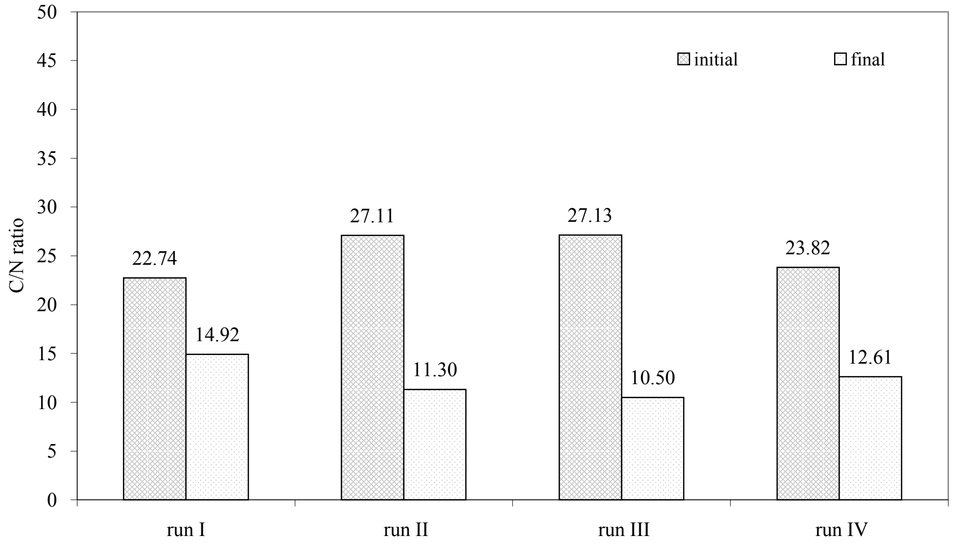


Figure 4.11 Changes in C/N ratio of the composting mixture during each run

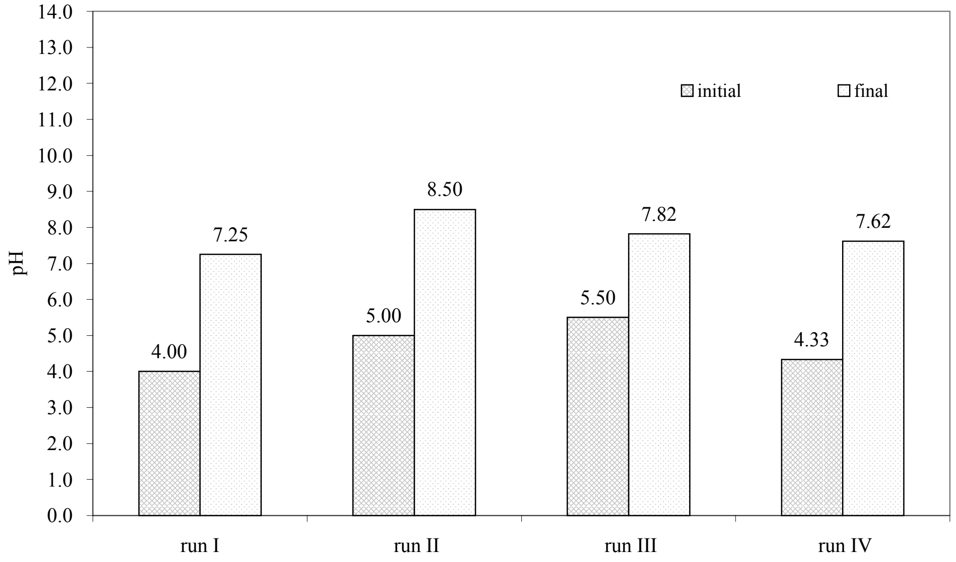


Figure 4.12 Changes in pH of the composting mixture during each run

4.4 Temperature Profiles

The temperature profiles of each composting run were obtained by recording the temperature (^{o}C) along with time (hours/days) for each point inside the composter as shown in Figure 4.13 (see Appendix E). This figure shows the cross-section of the composter, which has a diameter of 50 cm. Points r-1 and r+1 are located at 12.5 cm from the center on both sides of the radial axis. Points r-2 and r+2 are located at the surface boundary of the composter.

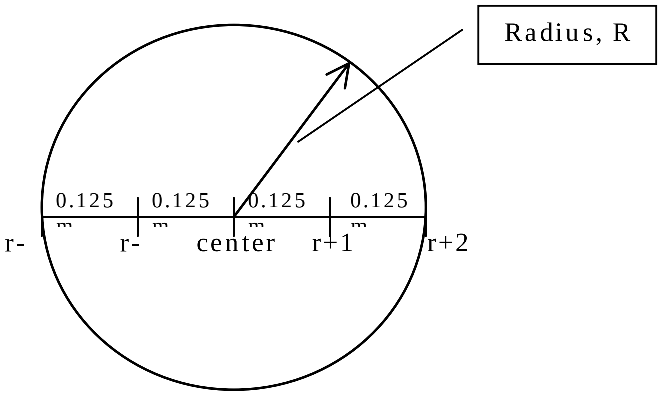


Figure 4.13 Points of temperature measurement inside the composter

Temperature profiles at the above mentioned points during the four experimental runs are shown in Figures 4.14-17. Figure 4.18 shows the comparison of four different runs and Table 4.6 presents the initial and maximum temperatures and the time to reach the maximum temperatures of all composting runs. Temperature increased rapidly during the initial state (first few days) of the composting process and continued increasing until it had reached the maximum. The highest temperature for each experimental run occurred at the center of the composter. The maximum temperatures at other point were lower along the radial directions. That is, the temperature distributed along the radial directions from the center of the composting mass to the periphery of the composters. Thus, $T_{center} > T_{r-1}$ and $T_{r+1} > T_{r-2}$ and T_{r+2}, as the air diffused from the center throughout the composting mass to the composter's periphery. Increased temperature in the reactors indicated heat generation during the composting process. The relationship of temperature and time was applied to estimate heat generation rate.

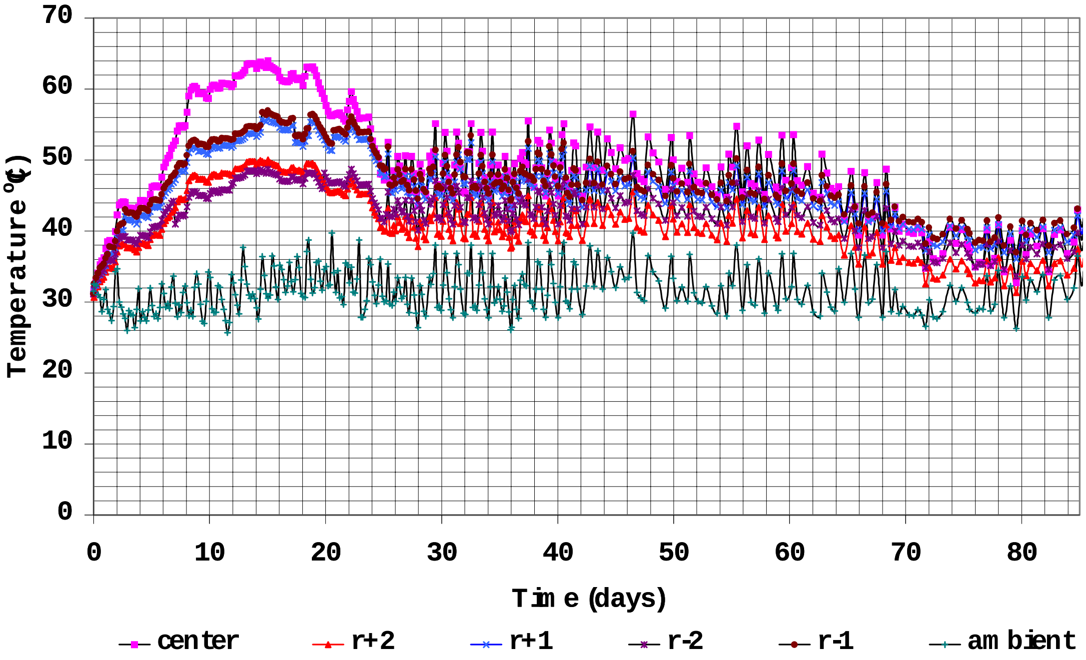


Figure 4.14 Temperature profiles for RUN I

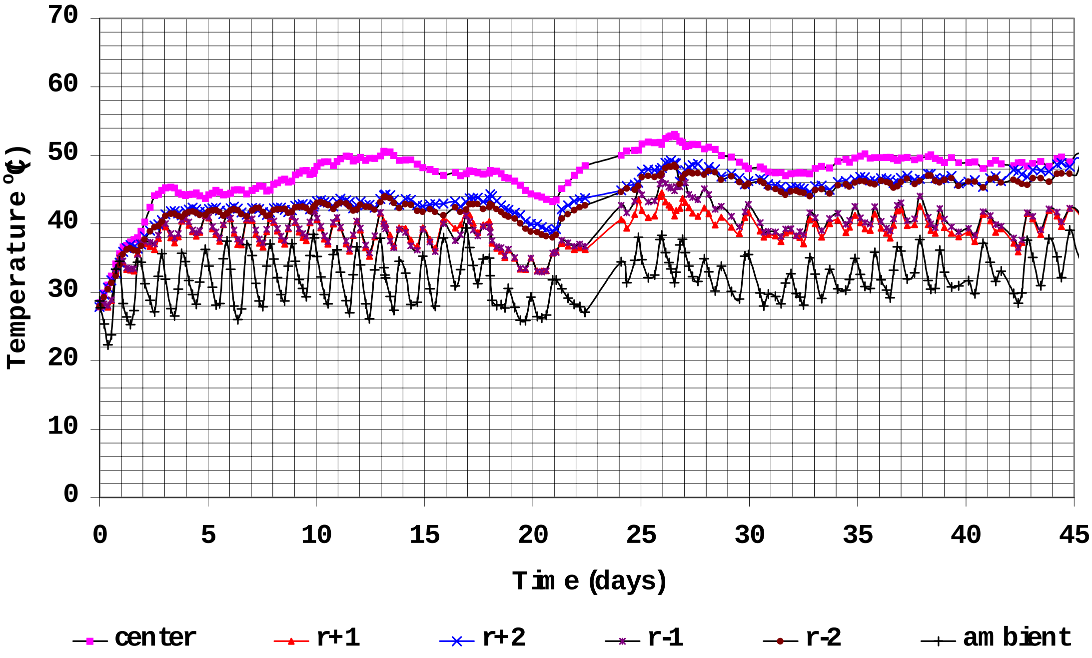


Figure 4.15 Temperature profiles for RUN II

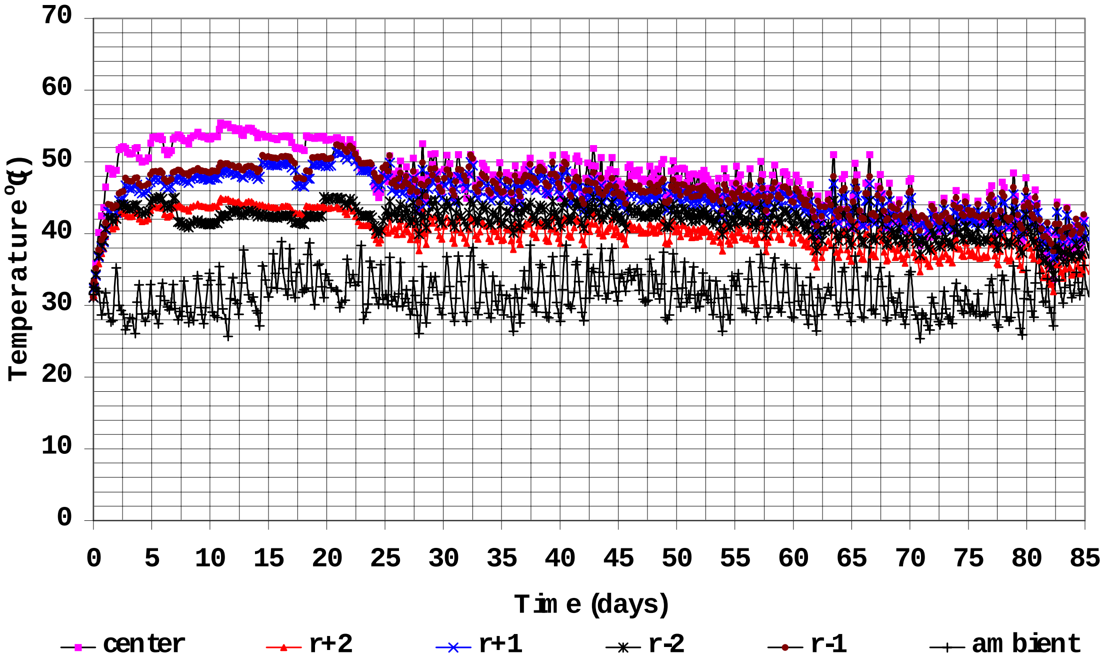


Figure 4.16 Temperature profiles for RUN III

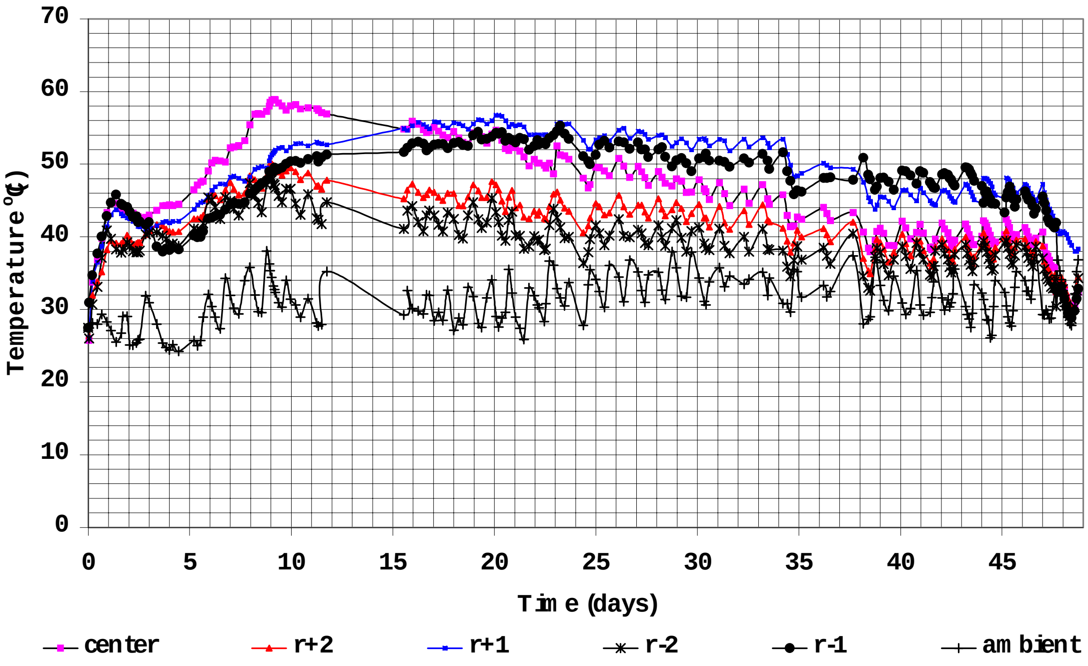


Figure 4.17 Temperature profiles for RUN IV

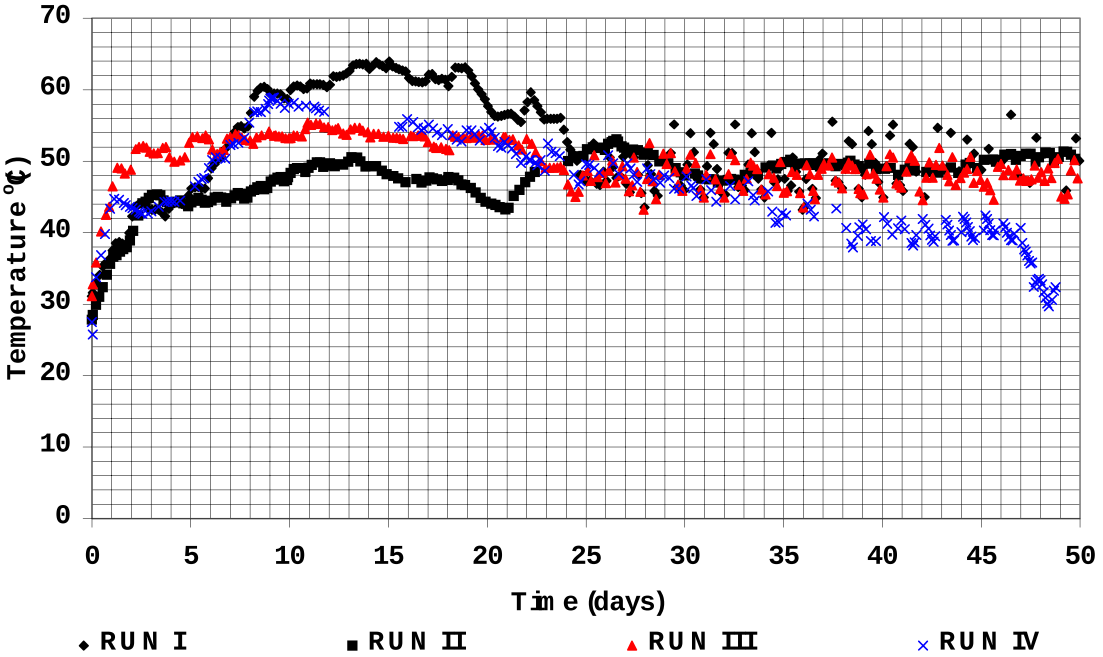


Figure 4.18 Temperature profiles of four experimental runs

Aeration was a significant parameter affecting temperature distribution in composting process. Forced aeration provided from the center of the composters penetrated throughout the composting mass along radial directions. The rate of composting process is related to the amount of air available for the aerobic microorganisms. The change in temperature of the mass represents the activities of these organisms indicating organic material biodegradation. Thus, temperature distribution in the composters was dependent on the amount of air penetrating to the mass. Aeration also effected the rate of temperature change with time as shown in Figure 4.18. During the first 2 days, RUN III and IV had faster rate of temperature rising, in contrast, RUN I and II showed slower rate.

Environmental temperatures influenced the fluctuations in temperature profiles for all experimental runs. The air blowing into each composter was not temperature controlled, thus, fluctuations occurred in all profiles. RUN II and IV clearly indicated effects of environmental temperature. The ambient temperature gradually dropped during day 18-20 in RUN II and day 2-4 in RUN IV. The microorganisms metabolic activity stopped during the cool air feeding period and started again when the temperature increased.

Table 4.6 Initial and maximum temperatures of the four runs

Points	RUN I		RUN II						RUN III		RUN IV	
			1st peak		2nd peak		Average					
	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)	Maximum temperature (^{o}C)	Time to reach maximum Temperature (days)
Center	64.0	15	50.6	13	53.1	27	51.8	20	55.4	11	58.9	9
r+2	50.0	15	44.3	18	49.2	26	46.8	22	44.9	11	50.1	9
r+1	56.0	15	42.0	17	44.5	26	43.2	21	51.4	21	56.8	20
r-2	48.8	22	44.0	13	48.6	27	46.3	20	45.5	28	48.5	9
r-1	57.0	15	41.9	10	46.9	27	44.4	18	52.4	11	55.3	23
Average room temperature (^{o}C)		31.5	33.1						31.5		30.9	
Initial temperature of composting mass (^{o}C)		31.1	27.8						31.1		27.5	
Aeration rate (m^3/day)		1.8	3.6						5.4		10.0	

In composting process, heat conduction was distributed within and between the organisms, water gases, and compost material cells. Higher aeration rate allowed faster rate of temperature increase with time. In contrast, it allowed lower maximum temperature. Thus, it could be said that the aeration rates may be adjusted for the composting process to optimize the biodegradation rates, which are temperature dependent. Moreover, the appropriate temperature required for an aerobic composting process must be in a thermophilic range (45-75°C). This temperature range is effective for pathogen killing.

Based on the results of temperature profiles of the four experimental runs it could be stated that, the three parameters during the composting process, aeration rate, maximum temperature, and rate of temperature change with time were interrelated. Figures 4.19 and 4.20 show the correlation of the maximum temperature with the time and aeration rates, respectively. The highest temperature occurred in RUN I with the lowest aeration rate. The fastest time duration to reach the maximum temperature was found in RUN IV with the highest aeration rate.

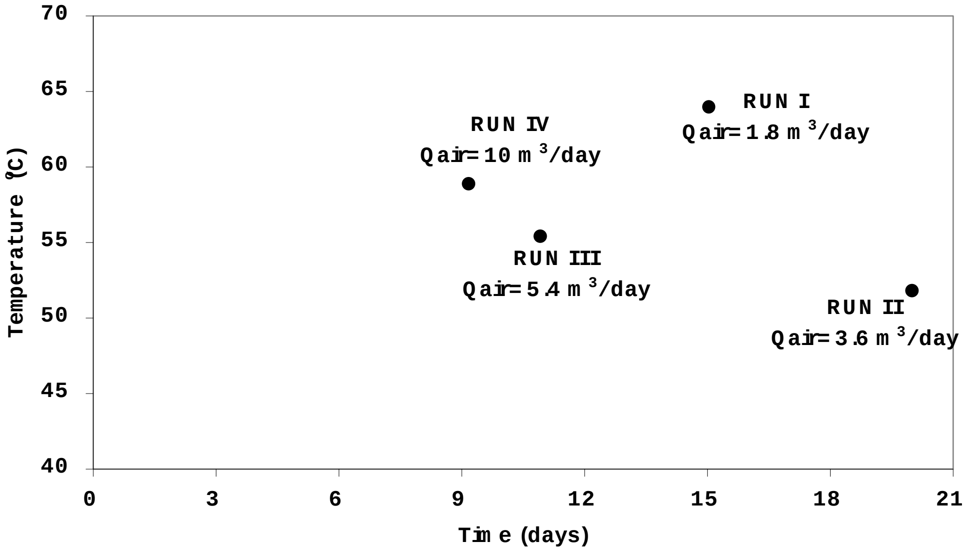


Figure 4.19 Correlation between maximum temperature and time during four composting runs

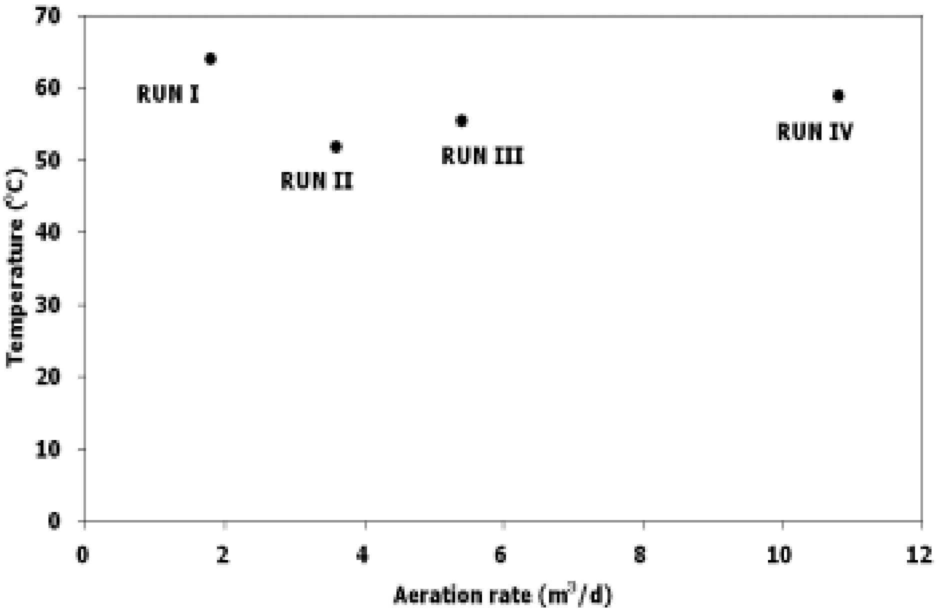


Figure 4.20 Correlation between maximum temperature and aeration rate in each experimental run

4.5 Physical and Thermal Properties

Thermal conductivity, (k): A voltage, V, of 3 volts applied to the heat probe produced a current, I, of 1.5 amperes. A calibration curve was obtained to calculate the effective length, L, from the slope of temperature vs. ln (time) by utilizing agar gel (slope, $m = \frac{IV}{4\pi kL}$), which has thermal conductivity, k = 0.61 watt/m/°C. The effective length of the thermal conductivity probe was found to be 0.1822 m. The experiment was conducted for four different samples of composted material with various ages (different moisture content). The results are shown in Table 4.7. Figure 4.20 shows the relationship between thermal conductivity and moisture content of the compost material (also see Appendix F).

Moisture content of the compost material ranged broadly between 45% - 85%, which averaged to be 65 %. The average thermal conductivity, 0.53 watt/m/°C, was used in this study.

Thermal diffusivity, α: The thermal diffusivity constant in the unit of m^2/s can be defined as $\frac{k}{c\rho}$. The value of specific heat capacity, c, was taken to be 3.18 kJ/kg-^oC, bulk density, ρ, of the waste sample from the average of several measurements, was found to be 740 kg/m^3. Thus, the thermal diffusivity of the organic waste material used for this study was calculated to be 2×10^{-7} m^2/s.

Table 4.7 Results of thermal conductivity measurement

Sample	Sample age (days)	Room Temp. (^oC)	Slope m	Thermal conductivity k (watt / m / ^oC)	Moisture Content (%)
Agar Gel	-	24.83	3.22	0.61	-
Sample 1	26	24.94	9.84	0.20	22.68
Sample 2	18	24.97	3.60	0.55	52.24
Sample 3	3	24.92	3.59	0.55	52.53
Sample 4	0	24.88	3.94	0.50	47.57

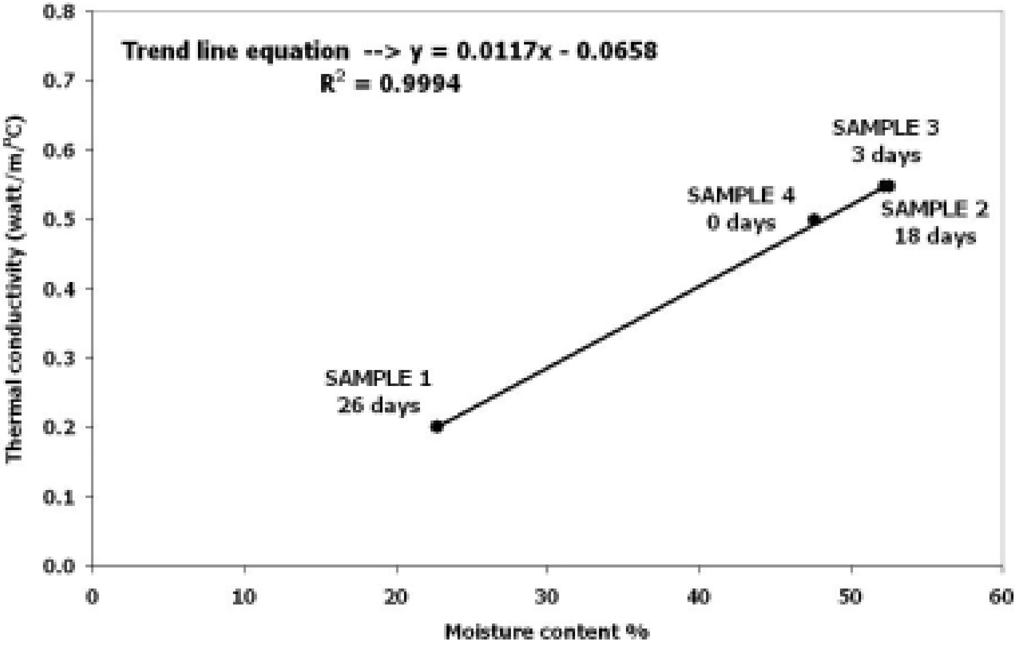


Figure 4.21 Correlation between thermal conductivity and moisture content

4.6 Heat generation

The first step in a finite-difference solution scheme was to discretize the spatial and time coordinates to form a mesh of nodes. Consider radial heat transfer in a long, solid cylinder of radius r = R in which heat is generated as $\overset{\circ}{q}(r)$ W/m^3. The region $0 \leq r \leq R$ may be divided into N cylindrical subregions, each of thickness $\Delta r = \frac{R}{N}$ as shown in Figure 4.21.

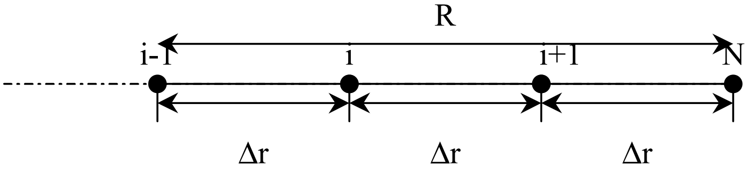


Figure 4.22 Nodal positions in the cylinder

Next, finite-difference approximations were made to derivatives appearing in the heat equation (Chapter 2) to convert the differential equation to an algebraic difference equation. Alternatively, the difference equation can be constructed by applying the energy conservation principle directly to a volume element surrounding the node. For transient conditions, temperatures at the current time step may be found directly using values at the preceding time step. Accuracy of a finite-difference approximation increases with number of nodes (Mills, 1999).

Explicit form of finite-difference approximations for one-dimensional unsteady conditions was used. Therefore, equation (2.15),

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

was substituted with,

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{(\Delta r)^2}\left[T_{i-1}^{p} + T_{i+1}^{p} - 2T_i^{p}\right]$$

$$\frac{\partial T}{\partial r} = \frac{T_{i+1}^{p} - T_{i-1}^{p}}{2(\Delta r)}$$

$$\frac{\partial T}{\partial t} = \frac{T_i^{p+1} - T_i^{p}}{\Delta t}$$

Where, i or j = nodal positions
p = time steps
T_i^p = temperature of point i at time p
T_{i-1}^p = temperature of point i-1 at time p
T_{i+1}^p = temperature of point i+1 at time p
T_i^{p+1} = temperature of point i at time p+1
Δt = duration between time p and p+1

As a result, the *finite-difference form* (Özişik, 1985) of heat equation can be written as:

$$\frac{1}{(\Delta r)^2}\left[T_{i-1}^p + T_{i+1}^p - 2T_i^p\right] + \frac{1}{r}\left[\frac{T_{i+1}^p - T_{i-1}^p}{2(\Delta r)}\right] + \frac{\overset{\circ}{q}}{k} = \frac{1}{\alpha}\left[\frac{T_i^{p+1} - T_i^p}{\Delta t}\right] \qquad (4.1)$$

In order to solve the heat equation, boundary and initial conditions were used to evaluate integration constants. In well-insulated system, heat flux at the boundary is simply known (assumed) to be zero. Transient heat problems usually require specification of an initial condition, which simply means that the temperature throughout the mass body must be known at an instant of time before its subsequent variation with time can be determined (Mills, 1999). For this study, uniform initial temperatures throughout the mass were taken to be known, thus, $T_{i-1} = T_i = T_{i+1}$.

Let $m = \frac{\alpha \Delta t}{(\Delta r)^2}$, and Fourier Number, which is a dimensionless time variable, $\frac{\alpha t}{L^2} = 0.25 = \frac{\alpha \Delta t}{(\Delta r)^2}$, thus, $\Delta t = \frac{0.25(\Delta r)^2}{\alpha}$. In addition, h = heat transfer coefficient (specific conductivity) and T_∞ = ambient temperature. These values were utilized as follows:

Equation for interior nodes:

$$T_i^{p+1} = \frac{m}{2}\left[\left(2 + \frac{\Delta r}{r_i}\right)T_{i+1}^p + \left(2 - \frac{\Delta r}{r_i}\right)T_{i-1}^p + \left(\frac{2}{m} - 4\right)T_i^p + \left(\frac{2(\Delta r)^2 \overset{\circ}{q}}{k}\right)\right] \qquad (4.2)$$

Equation for center node: At the center, $r = 0$ and $T_{i-1} = T_{i+1}$. After some rearrangement of the terms, equation (4.1) yields

$$T_i^{p+1} = 4mT_{i+1}^p + \left(1 - 4mT_i^p\right) + \left(\frac{m(\Delta r)^2 \overset{\circ}{q}}{k}\right) \tag{4.3}$$

Equation for surface node: Equation for node N on the surface was determined by applying $T_i = \dfrac{T_{i-1} + \dfrac{h\Delta r}{k} T_\infty}{1 + \dfrac{h\Delta r}{k}}$ at the boundary and by taking into a consideration the boundary condition. After the rearrangement of the terms,

$$T_N^{p+1} = \frac{T_{N-1}^{p+1} + \dfrac{h\Delta r T_\infty}{k} + \dfrac{1}{2}\dfrac{(\Delta r)^2 h \overset{\circ}{q}}{k}}{1 + \dfrac{h\Delta r}{k}} \tag{4.4}$$

Equations (4.1)-(4.4) were used in a computer program to simulate the temperature distribution of the composting mass during the biodegradation process of each run. The computer program is shown in Appendix G. Heat generated per unit volume, $\overset{\circ}{q}$, were assumed for each simulation run, and the rates of temperature change with time, $\dfrac{\partial T}{\partial t}$, were compared with the experimental ones. Correlation between the heat generation ($\overset{\circ}{q}$), with time (t), for each experimental run is shown in Table 4.8 and Figure 4.22.

Table 4.8 Heat generated during various time periods in four experimental runs

Time		Heat generated							
Day	Hour	RUN I		RUN II		RUN III		RUN IV	
		W/m^3	Btu/h-kg TVS	W/m^3	Btu/h-kg TVS	W/m^3	Btu/h-kg TVS	W/m^3	Btu/h-kg TVS
0	0	-	-	-	-	-	-	-	-
1	24	40.6	664.1	221.4	3,621.2	59.9	979.7	483.7	7,911.4
2	48	113.1	1,849.9	124.0	2,028.1	185.7	3,037.3	109.5	1,791.0
3	72	133.0	2,175.3	156.3	2,556.4	236.0	3,860.0	190.8	3,120.7
4	96	130.7	2,137.7	153.3	2,507.4	242.0	3,958.1	210.7	3,446.2
5	120	127.2	2,080.5	150.0	2,453.4	235.3	3,848.6	208.7	3,413.5
6	144	122.2	1,998.7	142.5	2,330.7	216.9	3,547.6	181.7	2,971.9
7	168	111.2	1,818.8	135.1	2,209.7	206.5	3,377.5	164.8	2,695.5
8	192	101.9	1,666.7	123.4	2,018.3	191.4	3,130.5	145.2	2,374.9
9	216	95.8	1,566.9	112.7	1,843.3	178.9	2,926.1	132.3	2,163.9
10	240	98.1	1,604.5	103.4	1,691.2	168.0	2,747.8	128.8	2,106.7
11	264	97.0	1,586.5	96.4	1,576.7	155.7	2,546.6	124.8	2,041.2
12	288	97.5	1,594.7	87.2	1,426.2	147.6	2,414.1	122.7	2,006.9
13	312	101.4	1,658.5	85.0	1,390.3	140.3	2,294.7	125.7	2,055.9
14	336	101.1	1,653.6	81.6	1,334.6	135.1	2,209.7	124.6	2,038.0
15	360	101.3	1,656.9	87.4	1,429.5	129.0	2,109.9	121.9	1,993.8

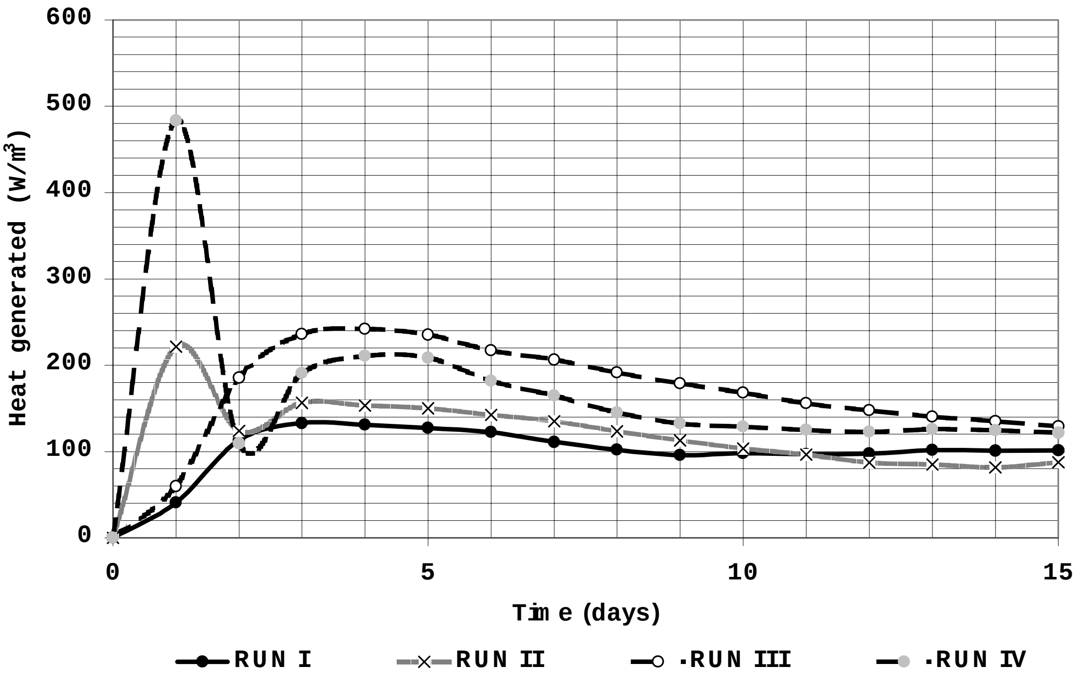


Figure 4.23 Correlation between heat generated and time during four composting runs

Heat was rapidly generated during the first few days and continued increasing up to a maximum point, then decreased down to reach stable state. The highest heat generation ($\overset{\circ}{q}$) occurred in RUN IV, with the highest aeration rate. The higher $\overset{\circ}{q}$ indicated faster rate of temperature increase with time. From this study, the maximum heat generated obtained were 133, 221.4, 242, and 483.7 W/m^3 for RUN I, II, III and IV, respectively.

The typical proximate energy data found in food waste is 5,983 Btu/lb dry solids (13,187 Btu/kg TS and 7,180 Btu/lb dry ash-free) and 6,503 Btu/lb dry solids 14,333 Btu/kg TS and 6,585 Btu/kg dry ash-free) for yard waste (Tchobanoglous, 1993). From the amount of heat generated, maximum energy content obtained during four experimental runs were 2,080.5, 2,556.4, 3,958.1 and 7,911.4 Btu/h-kg TVS for RUN I, II, III and IV, respectively.

Chapter V

Conclusions and Recommendations

5.1 Conclusions

Four composting runs were conducted using mixture of food waste and yard waste. The organic waste mixture ratio was 1:0.0286 by weight for food waste: yard waste. The initial C/N ratio ranged between 22-28:1, which was adequate for the biodegradation process. Four different aeration rates, 1.8 m^3/d, 3.6 m^3/d, 5.4 m^3/d, and 10 m^3/d, were used for RUN I, RUN II, RUN III, and RUN IV, respectively.

The main research objectives were to study the temperature distribution and heat generation in an aerobic composting process. Several parameters were controlled and assumed. Food waste characteristics are related to several factors, for example, climate, seasons, and cultural impact, which vary widely. A mixture of selected food waste was used to maintain somewhat constant initial values of its characteristic. Effective microorganisms, known as E.M., were used for this study. Equal amount of E.M. was added to the mixed organic waste prior to composting runs to ensure the aerobic conditions. Many studies had been completed mainly for effects of E.M., nevertheless, no convinced conclusion had been brought up. E.M. is believed to stimulate the biodegradation process and it is sounded for odor control. Since the equal amount was added to each experimental run, E.M. was not a factor effecting this study.

Compost product characteristics were determined after each experimental run. Decrease in organic matter and moisture content indicated the decomposition and stabilization of the organic waste. C/N ratio of the final product ranged between 11-15:1 and total volatile solids ranged between 47-60 %. The product's moisture content was still high comparing to soil and other commercial solid fertilizers. Considering the end products, RUN II was the best run considering the end product; the highest organic carbon was decreased in this experimental setup.

Type K thermocouples and data loggers recorded temperature and time at different points inside the composters. Temperature profiles within the composting mass were monitored. Temperatures increased rapidly at the initial state of composting process and continued increasing up to the maximum. Organic waste stabilization stage was accomplished when the temperatures decreased down to the room temperature. The maximum temperatures for all composting runs ranged between 50-64 ^{o}C, which were within thermophilic range. Temperature did not equally distribute throughout the composting mass, thus, a uniform distribution was assumed for this study. The assumption was made based on the experimental results. Temperature differences along the radial axis were neglected.

Although, the reactors were insulated and very much closed, the air provided to the composting process was not temperature controlled. The temperature recorded fluctuated according to the environmental temperature. The fluctuations were neglected to have clear understanding for the temperature profiles. Fluctuation also appeared in aeration rates. The air compressor collects and compresses air inside the container while providing air to the composters. Once the air pressure inside the compressor decreases to a selected point, then, the compressor automatically starts collecting air again. This fluctuation may also cause temperature to fluctuate.

The amount of air supplied throughout the process was an important factor affecting the rate of temperature change with time and the maximum temperature. Temperature is an important factor for microorganisms growth, which carried out the biodegradation process and pathogen kills. It also indicates the stability of the compost product. Optimum air supplied for each composting process is, therefore, very necessary for composting process.

Thermal properties were also obtained from the laboratory experiments and calculations. Organic waste samples' average thermal conductivity, k, was obtained to be 0.53 W/m/^{o}C and thermal diffusivity, α, was calculated to be 2.7×10^{-7} m^2/s.

Mixed organic waste samples were assumed to be homogeneous, thus, thermal properties of the material were constant. These thermal properties were specific heat capacity, thermal conductivity, and thermal diffusivity. Likewise, samples' moisture content during the biodegradation changes in accordance to time and state of the process. From this study, it could be observed that thermal conductivity of the samples were clearly influenced by moisture content. However, for simplicity, the samples were assumed to be isotropic, for which the conductivity is the same in all directions and time.

One-dimensional heat balance equation was derived for cylindrical coordinate system. Explicit finite different method was used to develop numerical scheme for determining the heat generation in the composting process. Three equations for interior nodes, center node, and surface node were used in the computer program to estimate heat generated during the process. It is realized that the condition may vary in actual practice with regard to the heat generation and dissipation during the composting process. The modified insulated reactors were designed to prohibit and mitigate heat lost to the environment due to air conduction. Therefore, heat lost throughout the process was neglected.

The maximum heat generated during RUN I, RUN II, RUN III, and RUN IV were 133, 221.4, 242, and 483.7 W/m^3, respectively. Thus, the energy content were 2,080.5, 2,556.4, 3,958.1 and 7,911.4 Btu/hr-kg TVS for RUN I, II, III and IV, respectively. Aeration rate was an important factor for heat generation in the composting process.

Temperatures and heat output is one way of assessing compost quality. Temperature profiles showed the understanding of the process conditions and pathogen inactivation could be assessed. Heat produced can also be a measure of final products' suitability. Relationship between temperature distribution change with respect to time and heat generated was obtained. The relationship between different aeration rates and the temperature profiles and heat output in composting process were assessed. Effects of the heat generated on the temperature profiles in composting process were understood. They could be used for effectiveness assessment. Heat output in the process could also be used to estimated the temperatures changes in the system. Nevertheless, temperature profiles can be used to estimated the heat evolution in the composting process.

5.2 Recommendations

This study concerned only one-dimensional distribution, three-dimension may be applied to explicit finite different method for better solution of heat generation.

Three-dimension Cartesian and cylindrical system give different solution, and both must be applied to have a complete view of temperature distribution. A designed and engineered system must be used to prevent unnecessary cost. Energy input and output can be useful to optimize the system. This experimental setup can also be applied to any biological processes that produce heat.

Moreover, temperature distribution is significantly important for microbial growth and activities, including pathogen kills in a static unit. In a static composting unit, forced air supply to the system can be distributed for higher efficiency. Several air diffusers can be used to spread the air all through the body, nevertheless, high aeration can cause heat to escape from the system and thus the system temperature cannot reach thermophilic state. In other words, system optimization must be studied deeply.

Composting is a natural process in the ecosystem under suitable conditions. Any organic material can be biodegraded under the presence of microorganisms (aerobic and anaerobic). Considering heat generated in composting process, landfill can be a major source for biodegradation. Heat generation and temperature distribution in the landfill mass should be studied. The dangers may arise when hazardous wastes react; heat catalyzes some chemical reactions.

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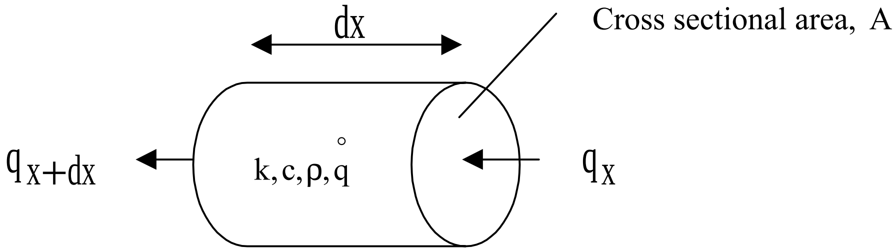
Appendix A

Fourier's Equation

Fourier's Equation

One-dimensional heat transfer (Rao, 1999):



Heat inflow during time dt + Heat generated by internal sources during dt = Heat outflow during dt + Change in internal energy during dt

$$q_x dt + \overset{\circ}{q}\, dxdt = q_{x+dx} dt + \rho c dTdx$$

$$q_x = -kA\frac{\partial T}{\partial x}$$

$$q_{x+dx} = -kA\frac{\partial T}{\partial x} - \frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)dx$$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)+\left(\overset{\circ}{q}\, dxdtA\right)=\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt+\left(c\rho dTdxA\right)$$

The constant $\alpha = \frac{k}{c\rho}$, then $c\rho = \frac{k}{\alpha}$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)+\left(\overset{\circ}{q}\, dxdtA\right)=\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt+\left(\frac{k}{\alpha}dTdxA\right)$$

$$\left(-kA\frac{\partial T}{\partial x}dt\right)-\left[-kA\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}dx\right)\right]dt=\left(\frac{k}{\alpha}dTdxA\right)-\left(\overset{\circ}{q}\, dxdtA\right)$$

$$kA\frac{\partial T}{\partial x}\left(-dt+dt+\frac{\partial}{\partial x}dxdt\right)=A\left[\left(\frac{k}{\alpha}dTdx\right)-\left(\overset{\circ}{q}\, dxdt\right)\right]$$

$$k\frac{\partial^2 T}{\partial x^2}dxdt+\overset{\circ}{q}\, dxdt=\frac{k}{\alpha}dTdx$$

Dividing each term by $kdxdt$, we obtain

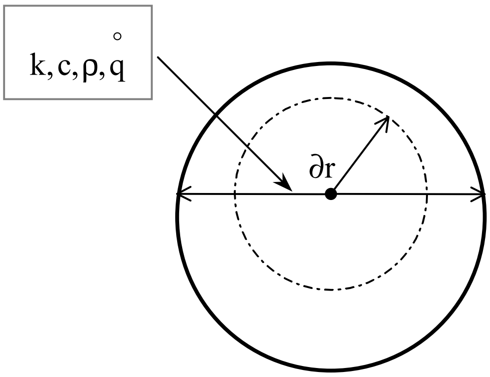
$$\frac{\partial^2 T}{\partial x^2}+\frac{\overset{\circ}{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

If cylindrical coordinate system is used instead of the Cartesian system and

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$$

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{r}\left(r\frac{\partial^2 T}{\partial r^2}+\frac{\partial r}{\partial r}\frac{\partial T}{\partial r}\right)$$

$$\frac{\partial^2 T}{\partial x^2}=\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}$$



$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\overset{\circ}{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Appendix B

Samples' Characteristics

Table B.1 Samples’ charateristics

date	sample	Dish (g)	wet wt. (g)	dry wt. (g)	ignited (g)	% moisture	% solids	% VS	% ash	% C	% N	C/N ratio	pH
11-nov	food waste (No.1)	48.51	118.17	61.65	51.30	81.14	18.86	78.77	21.23	39.60	1.79	22.18	
	food waste (No.2)	46.77	149.33	66.77	51.11	80.50	19.50	78.30	21.70	39.16	1.79	21.85	
	food waste (No.3)	56.07	141.01	72.30	58.90	80.89	19.11	82.56	17.44	39.18	1.79	21.84	
	food waste (No.4)	38.36	122.83	54.43	41.33	80.98	19.02	81.52	18.48	38.92	1.74	22.37	
	food waste (No.5)	45.78	117.02	59.12	48.20	81.27	18.73	81.86	18.14	39.24	1.79	21.93	
	average					80.96	19.04	80.60	19.40	39.22	1.78	22.04	
	yard waste (No.1)	42.57	47.76	45.16	42.95	50.10	49.90	85.33	14.67	40.02	1.22	32.91	
	yard waste (No.2)	40.40	47.23	43.77	41.08	50.66	49.34	79.82	20.18	40.14	1.23	32.53	
	yard waste (No.3)	34.69	44.24	39.42	35.62	50.47	49.53	80.34	19.66	41.70	1.31	31.83	
	yard waste (No.4)	47.53	53.81	50.62	48.19	50.80	49.20	78.64	21.36	40.00	1.21	32.95	
	yard waste (No.5)	37.24	44.48	40.81	38.00	50.69	49.31	78.71	21.29	40.46	1.27	31.96	
	average					50.54	49.46	80.57	19.43	40.46	1.25	32.44	
18-feb	food waste (NO.1) - run I	32.94	93.87	42.46	34.00	84.38	15.62	88.87	11.13	40.73	2.04	19.93	
	food waste (NO.2) - run I	31.09	104.30	43.14	32.59	83.54	16.46	87.55	12.45	40.43	1.96	20.59	
	food waste (NO.3) - run I	31.32	97.32	42.19	32.50	83.53	16.47	89.14	10.86	41.00	1.94	21.17	
	average					83.82	16.18	88.52	11.48	40.72	1.98	20.56	
	yard waste (No.1) - run I	47.54	49.53	49.40	47.80	6.53	93.47	86.02	13.98	39.23	1.18	33.39	
	yard waste (No.2) - run I	45.78	48.53	48.34	46.15	6.91	93.09	85.55	14.45	38.61	1.11	34.69	
	yard waste (No.3) - run I	31.22	33.60	33.44	31.54	6.72	93.28	85.59	14.41	38.68	1.10	35.32	
	average					6.72	93.28	85.72	14.28	38.84	1.13	34.47	
	mixed (No.1) - run I	49.53	71.39	53.65	-	81.15	18.85	-	-	37.81	1.71	22.10	
	mixed (No.2) - run I	48.53	104.92	58.94	48.96	81.54	18.46	95.87	4.13	38.09	1.61	23.70	
	mixed (No.3) - run I	33.60	88.40	42.89	-	83.05	16.95	-	-	37.61	1.68	22.43	
	average					81.91	18.09	95.87	4.13	37.84	1.67	22.74	4.00

Table B.1 Samples' charateristics (continued)

date	sample	dish (g)	wet wt. (g)	dry wt. (g)	ignited (g)	% moisture	% solids	% VS	% ash	% C	% N	C/N ratio	pH
25-Apr	run I after 66 days (NO.1)	30.08	74.29	46.47	39.00	62.93	37.07	45.58	54.42	23.89	1.62	14.78	7.00
	run I after 66 days (NO.2)	40.41	80.30	55.20	47.31	62.92	37.08	53.35	46.65	23.86	1.60	14.96	7.50
	run I after 66 days (NO.3)	28.82	66.17	43.90	37.17	59.63	40.37	44.63	55.37	23.59	1.58	14.92	
	run I after 66 days (NO.4)	29.12	68.51	44.90	38.15	59.94	40.06	42.78	57.22	23.55	1.58	14.91	
	run I after 66 days (NO.5)	30.59	76.06	47.03	39.29	63.84	36.16	47.08	52.92	23.43	1.56	15.02	
	average					61.85	38.15	46.68	53.32	23.66	1.59	14.92	7.25
8-mar	food waste (NO.1) - run II	46.81	90.91	56.68	47.94	77.62	22.38	88.55	11.45	41.94	1.10	38.13	
	food waste (NO.2) - run II	45.78	84.63	55.12	46.83	75.96	24.04	88.76	11.24	41.68	1.06	39.43	
	food waste (NO.3) - run II	31.32	81.16	42.18	32.95	78.21	21.79	84.99	15.01	42.05	1.10	38.16	
	average					77.26	22.74	87.43	12.57	41.89	1.09	38.57	
	yard waste (No.1) - run II	32.94	37.54	37.06	33.68	10.43	89.57	82.04	17.96	40.21	1.48	27.21	
	yard waste (No.2) - run II	31.23	34.51	34.21	31.66	9.15	90.85	85.57	14.43	40.73	1.46	27.99	
	yard waste (No.3) - run II	32.10	36.61	36.21	32.75	8.87	91.13	84.18	15.82	40.69	1.46	27.89	
	average					9.48	90.52	83.93	16.07	40.54	1.46	27.70	
	mixed (No.1) - run II	47.55	76.15	55.17	48.77	73.36	26.64	83.99	16.01	40.24	1.54	26.11	
	mixed (No.2) - run II	28.26	62.59	37.47	29.49	73.17	26.83	86.64	13.36	40.10	1.41	28.48	
	mixed (No.3) - run II	31.11	47.17	34.43	31.48	79.33	20.67	88.86	11.14	40.47	1.51	26.73	
	average					75.29	24.71	86.50	13.50	40.27	1.49	27.11	5.00
25-Apr	run II after 49 days (NO.1)	34.93	56.73	41.87	37.83	68.17	31.83	58.21	41.79	24.36	2.15	11.31	8.00
	run II after 49 days (NO.2)	47.36	68.28	56.93	50.99	54.25	45.75	62.07	37.93	24.03	2.14	11.23	8.50
	run II after 49 days (NO.3)	30.46	53.83	37.71	33.54	68.98	31.02	57.52	42.48	23.88	2.12	11.25	8.50
	run II after 49 days (NO.4)	33.70	64.83	44.01	37.96	66.88	33.12	58.68	41.32	23.76	2.09	11.35	9.00
	run II after 49 days (NO.5)	33.08	67.39	43.95	37.22	68.32	31.68	61.91	38.09	23.75	2.09	11.38	
	average					65.32	34.68	59.68	40.32	23.96	2.12	11.30	8.50

Table B.1 Samples’ charateristics (continued)

date	sample	Dish (g)	wet wt. (g)	dry wt. (g)	ignited (g)	% moisture	% solids	% VS	% ash	% C	% N	C/N ratio	pH
19-Aug	mixed (No.1) - run III	27.51	74.67	38.58	29.66	76.53	23.47	80.58	19.42	42.05	1.60	26.36	6.00
	mixed (No.2) - run III	33.12	73.62	41.18	34.39	80.10	19.90	84.24	15.76	40.00	1.57	25.41	5.00
	mixed (No.3) - run III	33.71	68.91	41.28	34.90	78.49	21.51	84.28	15.72	38.22	1.29	29.60	
	mixed (No.4) - run III	34.03	84.86	45.92	36.00	76.61	23.39	83.43	16.57				
	average					77.93	22.07	83.13	16.87	40.09	1.49	27.13	5.50
15-Nov	run III after 87 days (NO.1)	7.59	46.83	18.00	11.52	73.47	26.53	62.25	37.75				9.00
	run III after 87 days (NO.2)	6.98	30.86	13.56	11.04	72.45	27.55	38.30	61.70				9.00
	run III after 87 days (NO.3)	7.69	53.57	20.27	13.59	72.58	27.42	53.10	46.90				9.00
	run III after 87 days (NO.4)	7.38	34.33	15.02	12.76	71.65	28.35	29.58	70.42				9.00
	run III after 87 days (NO.5)	7.38	44.01	17.06	10.18	73.57	26.43	71.07	28.93				9.00
	average					72.74	27.26	50.86	49.14				9.00
19-Aug	mixed (No.1) - run IV	29.14	42.24	32.08	29.63	77.56	22.44	83.33	16.67	40.26	1.70	23.72	4.00
	mixed (No.2) - run IV	47.37	71.24	53.48	48.38	74.40	25.60	83.47	16.53	41.61	1.76	23.63	4.00
	mixed (No.3) - run IV	28.85	50.08	32.61	29.44	82.29	17.71	84.31	15.69	41.17	1.71	24.10	5.00
	mixed (No.4) - run IV	30.48	54.19	36.78	31.61	73.43	26.57	82.06	17.94				
	average					76.92	23.08	83.29	16.71	41.01	1.72	23.82	4.33
15-Nov	run IV after 87 days (NO.1)	7.06	29.55	13.16	9.57	72.88	27.12	58.85	41.15				8.00
	run IV after 87 days (NO.2)	7.30	33.72	14.11	9.84	74.22	25.78	62.70	37.30				8.00
	run IV after 87 days (NO.3)	7.04	30.11	13.69	9.79	71.17	28.83	58.65	41.35				8.00
	run IV after 87 days (NO.4)	7.12	35.88	15.20	10.37	71.91	8.09	59.78	40.22				9.00
	run IV after 87 days (NO.5)	7.41	34.70	15.00	10.39	72.19	27.81	60.74	39.26				9.00
	average					72.47	27.53	60.14	39.86				8.40

Appendix C

Composting Waste Mixture Requirement

Mixture Requirement

Determination of the quantity of yard waste needed to be mixed with this waste to rise the C/N ratio of the mixture to 20-35:1, suitable for composting.

Sample Type	Bulk density, kg/L	% solids	% moisture	% ash	% VS	% N	% C	C/N ratio
Food waste	0.740	20	80	20	80	1.78	39.22	22.03
Yard waste	0.075	50	50	20	80	1.24	40.46	35.63

Mass balance:

For 1 kg of food waste: C content $= 1\times\frac{39.22}{100}$ kg

$= 0.3922$ kg

N content $= 1\times\frac{1.78}{100}\times\frac{1}{22.03}$ kg

$= 8.07989\times10^{-4}$ kg

For X kg of yard waste: C content $= x\times\left(\frac{40.46}{100}\right)$ kg

$= 0.4046\ X$ kg

N content $= x\times\left(\frac{1.24}{100}\right)\left(\frac{35.63}{1}\right)$ kg

$= 0.441812X$ kg

Therefore,

$$\frac{C}{N} = \frac{30}{1}$$

$$\frac{30}{1} = \frac{0.3922+0.4046x}{8.07989\times10^{-4}+0.441812x}$$

$$0.02423967+13.25436x = 0.3922+0.4046x$$

$$12.84976x = 0.36796033$$

$$X = 0.0286$$

$$X = 0.0286 \text{ kg of yard waste}$$

1 kg of fw requires mixing 0.0286 kg of yw to get the C/N ratio to 30:1

Total mass required:

The total volume of the composter:

$$\forall_{total} = \pi(r_{composter})^2(L_{composter}) - \pi(r_{pipe})^2(L_{pipe})$$

$$= \pi \times (0.25)^2 \times 1.0 - \pi \times (0.0127)^2 \times 1.0$$

$$\approx 0.196 \text{ m}^3$$

from $\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{\forall}$; $\quad \forall = \frac{m}{\rho}$

and $\frac{m_{fw}}{m_{yw}} = \frac{1}{0.0286} \frac{\text{kg}}{\text{kg}}$; $\quad m_{yw} = 0.0286 m_{fw}$

Mass balance:

$$\forall_{total} = \forall_{fw} + \forall_{yw}$$

$$0.196 \text{ m}^3 = \frac{m_{fw}}{\rho_{fw}} + \frac{m_{yw}}{\rho_{yw}}$$

$$= \frac{m_{fw}}{740 \frac{\text{kg}}{\text{m}^3}} + \frac{m_{yw}}{75 \frac{\text{kg}}{\text{m}^3}}$$

$$= \frac{m_{fw}}{740} + \frac{0.0286 m_{fw}}{75}$$

$$0.196 = \frac{75 m_{fw} + 21.164 m_{fw}}{55500}$$

$$10878 = 96.164 m_{fw}$$

$$m_{fw} = 113.12 \text{ kg}$$

$$m_{yw} = 3.24 \text{ kg}$$

Appendix D

Aeration Estimation

Aeration Estimation

Thermophilic reactions will require quantities of oxygen several times higher than those of mesophilic and maturation reactions. Additional amounts of air need to be supplied to compensate for loss to the atmosphere can be up to 95-99%.

Determination of the amount of oxygen required to oxidize x kg of yard waste aerobically.

Typical chemical composition of yard waste is $C_{23}H_{38}O_{17}N$

$$C_aH_bO_cN_d + \left(\frac{4a+b-2c+3d}{4}\right)O_2 \rightarrow aCO_2 + \left(\frac{b-3d}{2}\right)H_2O + dNH_3$$

$$C_{23}H_{38}O_{17}N + \left(\frac{4\times23+38-2\times17+3\times1}{4}\right)O_2 \rightarrow$$

$$23CO_2 + \left(\frac{38-3\times1}{2}\right)H_2O + NH_3$$

$$C_{23}H_{38}O_{17}N + 24.75O_2 \rightarrow 23CO_2 + 17.5H_2O + NH_3$$

Molecular weight of $C_{23}H_{38}O_{17}N$ = $12\times23+1\times38+16\times17+14$

= 600 g/mol

Molecular weight of $24.75O_2$ = $24.75\times16\times2$

= 792 g/mol

1 g of $C_{23}H_{38}O_{17}N$ requires: $O_2 = \frac{792}{600} \approx 1.32g$

BVS = $0.830 - (0.028)X$

Where BVS = biodegradable volatile solids

X = lignin content, % of VS

X_{yw} = 4.1 % of VS (Haug, 1993)

BVS = $0.083 - (0.028)\times4.1$

= 0.7152 = 71.25%

BVS mass of x kg yard waste:

= $x\,kg \times \%BVS$ = $xkg \times 0.8 \times \%VS$

= $x \times 0.0.7125 \times 0.8$ = $0.57x$ kg

Air required: $= \dfrac{(0.57x)\text{kgBVS}\times(1.32\times10^{-3})\dfrac{\text{kgO}_2}{\text{kgBVS}}}{0.23\dfrac{\text{kgO}_2}{\text{kgAir}}\times(1.2\times10^{-3})\dfrac{\text{kgAir}}{\text{L}}}$

$= (2.73X)$ L of air required

Assuming an oxygen demand is 35 % for the successive days of 5-days composting period, the aeration rate will be:

$$= \frac{(2.73x)\text{L}\times\dfrac{0.35}{\text{day}}}{1440\dfrac{\text{min}}{\text{day}}}$$

$$= (6.64\times10^{-4})x\frac{\text{L}}{\text{min}}; \qquad X = 3.24\text{ kg}$$

$$= 2.16\times10^{-3}\ \frac{\text{L}}{\text{min}}$$

Typical chemical composition of food waste is $C_{18}H_{26}O_{10}N$

$$C_{18}H_{26}O_{10}N+\left(\frac{4\times18+26-2\times10+3\times1}{4}\right)O_2\rightarrow$$

$$18CO_2+\left(\frac{18-3\times1}{2}\right)H_2O+NH_3$$

$$C_{18}H_{26}O_{10}N+20.25O_2\rightarrow18CO_2+7.5H_2O+NH_3$$

Determination of the amount of oxygen required to oxidize X kg of food waste aerobically.

Molecular weight of $C_{18}H_{26}O_{10}N=12\times18+1\times26+16\times10+14$

= 416 g/mol

Molecular weight of $20.25O_2=20.25\times16\times2$

= 648 g/mol

1 g of $C_{18}H_{26}O_{10}N$ requires: $O_2=\dfrac{648}{416}\approx1.558\text{g}$

X_{fw} = 0.4 % of VS (Haug, 1993)

BVS = $0.083 - (0.028) \times 0.4$

= 0.8188 = 81.88%

BVS mass of x kg yard waste:

$$= x\,\text{kg} \times \%\text{BVS} = x\text{kg} \times 0.8188 \times \%\text{VS}$$

$$= x \times 0.8188 \times 0.8 = 0.66\,x\,\text{kg}$$

Air required:
$$= \frac{(0.66x)\text{kgBVS} \times (1.558 \times 10^{-3})\dfrac{\text{kgO}_2}{\text{kgBVS}}}{0.23\dfrac{\text{kgO}_2}{\text{kgAir}} \times (1.2 \times 10^{-3})\dfrac{\text{kgAir}}{\text{L}}}$$

= $(3.73\,x)$ L of air required

Assuming an oxygen demand is 35 % for the successive days of 5-days composting period, the aeration rate will be:

$$= \frac{(3.73x)\text{L} \times \dfrac{0.35}{\text{day}}}{1440\dfrac{\text{min}}{\text{day}}}$$

$$= (9.07 \times 10^{-4})x\frac{\text{L}}{\text{min}}; \qquad x = 113.12\text{ kg}$$

$$= 0.1026\frac{\text{L}}{\text{min}}$$

Total air required

$$Q_{air_{fw}} + Q_{air_{yw}} = 0.1026 + 2.16 \times 10^{-3}\frac{\text{L}}{\text{min}}$$

$$\therefore Q_{air} = 0.10476\frac{\text{L}}{\text{min}} \text{ for actual requirement}$$

Appendix E

Temperatures Profiles

Table E.1 Temperature profiles for RUN I

time		Temperature					
days	hours	center	r+2	r+1	r-2	r-1	room
-	-	31.12	31.12	31.12	31.12	31.12	31.52
0.04	1	31.60	30.67	31.60	31.78	32.59	32.54
0.21	5	32.91	31.45	32.38	32.56	33.38	32.35
0.38	9	34.08	32.15	33.08	33.26	34.08	31.03
0.54	13	35.27	32.86	33.79	33.97	34.79	30.63
0.71	17	35.79	33.17	34.10	34.29	35.10	28.68
0.88	21	36.28	33.47	34.40	34.58	35.39	30.34
1.04	25	37.51	34.20	35.13	35.32	36.13	31.75
1.21	29	38.52	34.81	35.74	35.92	36.73	28.96
1.38	33	38.69	34.91	36.84	36.02	37.83	28.37
1.54	37	38.50	34.79	36.72	35.91	37.72	27.36
1.71	41	38.38	34.72	36.65	35.83	37.65	29.38
1.88	45	39.95	35.66	37.59	36.77	38.59	34.31
2.04	49	42.28	37.06	38.99	38.17	39.98	34.70
2.21	53	43.66	37.88	39.81	38.99	40.81	30.00
2.38	57	44.02	38.09	40.02	39.21	41.02	29.28
2.54	61	44.13	38.16	40.09	39.28	41.09	28.36
2.71	65	44.06	38.12	42.05	39.23	43.05	27.71
2.88	69	43.24	37.63	41.56	38.75	42.56	25.99
3.04	73	43.23	37.63	41.56	38.74	42.55	28.79
3.21	77	43.25	37.64	41.57	38.75	42.56	28.29
3.38	81	43.21	37.61	41.54	38.73	42.54	28.19
3.54	85	42.79	37.36	41.29	38.47	42.29	26.41
3.71	89	42.28	37.05	40.98	38.17	41.98	28.95
3.88	93	43.34	37.69	41.62	38.80	42.62	31.87
4.04	97	44.31	38.27	42.20	39.39	43.20	27.35
4.21	101	44.34	38.29	42.22	39.40	43.22	28.66
4.38	105	44.28	38.25	42.18	39.37	43.18	27.85
4.54	109	44.03	38.10	42.03	39.22	43.03	27.33
4.71	113	43.76	37.94	41.87	39.06	42.87	28.87
4.88	117	45.17	38.79	42.72	39.90	43.71	31.98
5.04	121	46.20	39.40	43.33	40.52	44.33	29.51
5.21	125	46.33	39.48	43.41	40.59	44.41	27.99
5.38	129	46.38	39.51	43.44	40.62	44.44	28.38
5.54	133	46.23	39.42	43.35	40.73	44.35	27.66

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
5.88	141	47.61	40.25	44.18	41.56	45.17	32.58
6.04	145	49.01	41.08	45.01	42.39	46.01	31.23
6.21	149	49.61	41.44	45.37	42.75	46.37	29.27
6.38	153	50.28	41.84	45.77	43.16	46.77	29.78
6.54	157	50.66	42.07	46.00	43.38	46.99	29.11
6.71	161	51.65	42.66	46.59	43.97	47.59	32.15
6.88	165	52.11	42.93	46.86	44.25	47.86	33.63
7.04	169	52.72	43.30	47.23	40.99	48.23	29.83
7.21	173	54.07	44.11	48.04	41.79	49.03	27.96
7.38	177	54.79	44.54	48.47	42.23	49.47	29.59
7.54	181	54.89	44.60	48.53	42.29	49.53	28.50
7.71	185	54.61	44.43	48.36	42.12	49.36	31.35
7.88	189	54.85	44.58	48.51	42.26	49.50	32.24
8.04	193	56.76	45.72	49.65	43.40	50.64	29.91
8.21	197	59.02	47.07	51.00	44.76	52.00	28.06
8.38	201	59.87	47.58	51.51	45.27	52.51	28.83
8.54	205	60.28	47.82	51.75	45.51	52.75	27.99
8.71	209	60.40	47.90	51.83	45.58	52.82	32.09
8.88	213	60.12	47.73	51.66	45.42	52.66	33.99
9.04	217	59.36	47.27	51.20	44.96	52.20	32.54
9.21	221	59.49	47.35	51.28	45.04	52.28	29.67
9.38	225	59.46	47.34	51.27	45.02	52.26	27.29
9.54	229	59.37	47.28	51.21	44.97	52.21	26.98
9.71	233	58.80	46.94	50.87	44.63	51.87	30.08
9.88	237	58.70	46.88	50.81	44.57	51.81	34.21
10.04	241	59.98	47.65	51.58	45.33	52.57	33.47
10.21	245	60.46	47.93	51.86	45.62	52.86	29.06
10.38	249	60.58	48.01	51.94	45.69	52.93	28.54
10.54	253	60.45	47.93	51.86	45.61	52.85	28.58
10.71	257	60.11	47.73	51.66	45.41	52.65	32.31
10.88	261	60.18	47.77	51.70	45.45	52.69	32.08
11.04	265	60.87	48.18	52.11	45.86	53.10	30.34
11.21	269	60.75	48.11	52.04	45.79	53.03	29.00
11.38	273	60.78	48.12	52.05	45.81	53.05	27.39
11.71	281	60.66	48.05	51.98	45.74	52.98	27.12

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
12.04	289	60.68	48.07	52.00	46.75	52.99	32.70
12.21	293	61.91	48.80	52.73	47.49	53.73	31.04
12.38	297	61.82	48.75	52.68	47.44	53.68	29.57
12.54	301	61.89	48.79	52.72	47.48	53.72	28.36
12.71	305	62.02	48.87	52.80	47.55	53.79	33.11
12.88	309	62.28	49.02	52.95	47.71	53.95	37.72
13.04	313	62.65	49.24	53.17	47.93	54.17	35.04
13.21	317	63.43	49.71	53.64	48.40	54.64	32.53
13.38	321	63.60	49.81	53.74	48.50	54.74	31.02
13.54	325	63.61	49.82	53.75	48.51	54.75	30.50
13.71	329	63.56	49.79	53.72	48.47	54.71	31.13
13.88	333	63.61	49.82	53.75	48.50	54.74	30.49
14.04	337	62.91	49.40	53.33	48.09	54.33	29.20
14.21	341	63.36	49.67	53.60	48.36	54.60	27.59
14.38	345	63.85	49.96	53.89	48.65	54.89	31.79
14.54	349	63.58	49.80	55.73	48.48	56.72	36.41
14.71	353	63.30	49.63	55.56	48.32	56.56	33.77
14.88	357	63.03	49.47	55.40	48.16	56.40	31.17
15.04	361	63.98	50.04	55.97	48.73	56.97	30.56
15.21	365	63.29	49.63	55.56	48.31	56.55	30.97
15.54	373	62.89	49.39	55.32	48.07	56.31	35.13
15.71	377	62.70	49.27	55.20	47.96	56.20	32.15
15.88	381	62.55	49.18	55.11	47.87	56.11	30.39
16.04	385	61.65	48.65	54.58	47.33	55.57	35.20
16.21	389	61.22	48.39	54.32	47.07	55.31	34.60
16.38	393	61.17	48.36	54.29	47.04	55.29	33.17
16.54	397	61.08	48.30	54.23	46.99	55.23	31.36
16.71	401	61.03	48.28	54.21	46.96	55.20	32.25
16.88	405	61.19	48.37	54.30	47.06	55.30	35.60
17.04	409	62.09	48.91	54.84	47.60	55.84	32.89
17.21	413	62.19	48.97	54.90	47.65	55.89	31.44
17.38	417	61.49	48.55	52.48	47.24	53.48	33.19
17.54	421	61.35	48.47	52.40	47.15	53.39	36.42
17.71	425	61.56	48.59	52.52	47.28	53.52	34.86
17.88	429	61.38	48.48	52.41	47.17	53.41	31.20

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
18.21	437	61.81	48.74	52.67	47.43	53.67	30.64
18.38	441	63.11	49.52	53.45	48.20	54.44	37.12
18.54	445	63.08	49.50	53.43	48.19	54.43	38.73
18.71	449	62.98	49.44	55.37	48.12	56.36	33.20
18.88	453	63.14	49.53	55.46	48.22	56.46	31.26
19.04	457	62.70	49.27	55.20	47.96	56.20	32.03
19.21	461	61.88	48.78	54.71	47.47	55.71	35.57
19.38	465	60.89	48.19	54.12	46.87	55.12	35.74
19.54	469	60.05	47.69	53.62	46.37	54.61	32.92
19.71	473	59.39	47.29	53.22	45.98	54.22	31.68
19.88	477	58.69	46.87	52.80	48.19	53.80	34.60
20.04	481	57.70	46.28	52.21	47.59	53.21	35.02
20.21	485	56.89	45.80	51.73	47.11	52.73	32.29
20.38	489	56.32	45.46	51.39	46.77	52.38	32.47
20.54	493	56.23	45.40	51.33	46.72	52.33	39.74
20.71	497	56.37	45.49	53.18	46.80	54.17	34.16
20.88	501	56.46	45.54	53.23	46.86	54.23	31.35
21.04	505	56.58	45.61	53.30	46.92	54.30	34.41
21.21	509	56.65	45.65	53.34	46.97	54.34	30.60
21.38	513	56.26	45.42	53.11	46.73	54.11	30.78
21.54	517	55.82	45.16	52.85	46.47	53.85	29.65
21.71	521	55.49	44.96	52.65	46.27	53.64	35.49
21.88	525	57.09	45.92	53.61	47.23	54.60	35.24
22.04	529	58.27	46.62	54.31	47.94	55.31	32.69
22.21	533	59.64	47.44	55.13	48.75	56.13	34.92
22.38	537	58.55	46.79	54.48	48.10	55.48	31.38
22.54	541	57.70	46.28	53.97	47.60	54.97	31.26
22.71	545	56.86	45.78	53.47	47.10	54.47	33.25
22.88	549	55.84	45.17	52.86	46.48	53.86	38.73
23.04	553	55.94	45.23	52.92	46.54	53.92	27.87
23.21	557	55.93	45.22	52.91	46.54	53.91	27.85
23.38	561	55.94	45.23	52.92	46.54	53.92	29.00
23.54	565	55.96	45.24	52.93	46.55	53.92	30.17
23.71	569	56.08	45.32	53.01	46.63	54.00	36.13
23.88	573	54.39	44.30	51.99	45.62	52.99	35.28

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
24.38	585	50.93	42.23	49.92	43.54	50.92	29.77
24.54	589	50.08	41.72	49.41	43.04	50.41	32.41
24.71	593	48.07	40.52	48.21	41.83	49.21	36.03
24.88	597	47.98	40.47	48.16	41.78	49.16	30.85
25.04	601	47.17	39.98	47.67	41.30	48.67	30.04
25.21	605	47.31	40.07	47.76	42.38	48.76	30.18
25.38	609	52.52	43.19	50.88	45.50	51.87	35.39
25.54	613	46.86	39.80	45.49	42.11	46.49	29.73
25.71	617	46.64	39.67	45.36	41.98	46.35	29.51
25.88	621	48.54	40.80	46.49	43.12	47.49	31.41
26.04	625	47.24	40.03	45.72	42.34	46.71	30.11
26.21	629	50.53	41.99	47.68	44.31	48.68	33.40
26.38	633	49.20	41.20	46.89	43.51	47.89	32.07
26.54	637	47.65	40.27	45.96	42.59	46.96	30.52
26.71	641	47.96	40.46	46.15	42.77	47.14	30.83
26.88	645	50.62	42.05	47.74	44.36	48.74	33.49
27.04	649	46.85	39.79	45.48	42.11	46.48	29.72
27.21	653	45.64	39.07	44.76	41.38	45.76	28.51
27.42	658	50.52	41.99	47.68	44.30	48.68	33.39
27.63	663	48.10	40.54	46.23	42.85	47.23	30.97
27.79	667	45.53	39.00	44.69	41.32	45.69	28.40
27.96	671	43.54	37.81	43.50	40.13	44.50	26.41
28.13	675	49.42	41.33	47.02	43.64	48.02	32.29
28.29	679	48.19	40.59	46.28	42.91	47.28	31.06
28.46	683	45.83	39.18	44.87	41.50	45.87	28.70
28.63	687	45.14	38.77	44.46	41.08	45.46	28.01
28.96	695	50.59	42.03	47.72	44.34	48.72	33.46
29.08	698	49.63	41.46	47.15	43.77	48.14	32.50
29.29	703	51.15	42.37	48.06	44.68	49.05	34.02
29.46	707	55.15	44.76	50.45	47.07	51.45	38.02
29.63	711	46.39	39.52	45.21	41.83	46.20	29.26
29.79	715	46.59	39.64	45.33	41.95	46.32	29.46
29.96	719	45.94	39.25	44.94	41.56	45.94	28.81
30.13	723	49.53	41.40	47.09	43.71	48.08	32.40
30.29	727	53.91	44.02	49.71	46.33	50.70	36.78

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
30.79	739	46.04	39.31	45.00	41.62	46.00	28.91
30.96	743	44.92	38.64	44.33	40.95	45.33	27.79
31.13	747	49.30	41.26	46.95	43.57	47.95	32.17
31.29	751	53.97	44.05	49.74	46.37	50.74	36.84
31.46	755	52.38	43.10	50.79	45.42	51.79	35.25
31.63	759	48.92	41.03	48.72	43.35	49.72	31.79
31.88	765	45.55	39.02	46.71	41.33	47.70	28.42
32.04	769	45.36	38.90	46.59	41.22	47.59	28.23
32.21	773	51.20	42.40	50.09	44.71	51.08	34.07
32.38	777	51.15	42.37	50.06	44.68	51.05	34.02
32.54	781	55.15	44.76	52.45	47.07	53.45	38.02
32.71	785	46.39	39.52	45.21	41.83	46.20	29.26
32.88	789	46.59	39.64	45.33	41.95	46.32	29.46
33.04	793	45.94	39.25	44.94	41.56	45.94	28.81
33.21	797	49.53	41.40	47.09	43.71	48.08	32.40
33.38	801	53.91	44.02	49.71	46.33	50.70	36.78
33.54	805	51.26	42.43	48.12	44.75	49.12	34.13
33.71	809	47.56	40.22	45.91	42.53	46.90	30.43
33.88	813	46.04	39.31	45.00	41.62	46.00	28.91
34.04	817	44.92	38.64	44.33	40.95	45.33	27.79
34.21	821	49.30	41.26	46.95	43.57	47.95	32.17
34.38	825	53.97	44.05	49.74	46.37	50.74	36.84
34.54	829	47.02	39.89	45.58	42.21	46.58	29.89
34.71	833	47.49	40.18	45.87	42.49	46.86	30.36
34.88	837	49.31	41.26	46.95	43.58	47.95	32.18
35.04	841	47.53	40.20	45.89	42.51	46.89	30.40
35.21	845	45.82	39.18	44.87	41.49	45.86	28.69
35.38	849	46.62	39.66	45.35	41.97	46.34	29.49
35.46	851	50.52	41.99	47.68	44.30	48.68	33.39
35.63	855	48.51	40.79	46.48	43.10	47.47	31.38
35.79	859	45.73	39.12	44.81	41.44	45.81	28.60
35.96	863	43.20	37.61	43.30	39.92	44.30	26.07
36.04	865	43.57	37.83	43.52	40.14	44.52	26.44
36.13	867	47.51	40.19	45.88	42.50	46.88	30.38
36.29	871	49.48	41.37	47.06	43.68	48.05	32.35

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
36.79	883	50.19	41.79	47.48	44.10	48.48	33.06
36.96	887	51.08	42.32	48.01	44.64	49.01	33.95
37.13	891	49.63	41.46	47.15	43.77	48.14	32.50
37.29	895	49.40	41.32	47.01	43.63	48.01	32.27
37.46	899	55.51	44.97	51.66	47.29	52.66	38.38
37.63	903	47.27	40.04	46.73	42.36	47.73	30.14
37.79	907	47.02	39.89	46.58	42.21	47.58	29.89
37.96	911	46.21	39.41	46.10	41.72	47.10	29.08
38.13	915	48.93	41.04	47.73	43.35	48.72	31.80
38.29	919	52.81	43.36	50.05	45.67	51.05	35.68
38.46	923	52.38	43.10	49.79	45.42	50.79	35.25
38.63	927	48.92	41.03	47.72	43.35	48.72	31.79
38.79	931	46.13	39.36	46.05	41.68	47.05	29.00
38.96	935	44.95	38.66	45.35	40.97	46.34	27.82
39.13	939	48.08	40.53	47.22	42.84	48.22	30.95
39.29	943	54.24	44.21	50.90	46.53	51.90	37.11
39.46	947	52.40	43.11	49.80	45.43	50.80	35.27
39.63	951	49.75	41.53	48.22	43.84	49.22	32.62
39.79	955	47.09	39.94	46.63	42.25	47.62	29.96
40.04	961	44.92	38.64	45.33	40.95	46.33	27.79
40.21	965	49.30	41.26	47.95	43.57	48.95	32.17
40.38	969	53.59	43.82	50.51	46.13	51.51	36.84
40.54	973	55.13	44.74	51.43	47.06	52.43	38.38
40.71	977	46.89	39.81	46.50	42.13	47.50	30.14
40.88	981	46.64	39.66	44.35	41.98	45.35	29.89
41.04	985	45.83	39.18	43.87	41.49	44.86	29.08
41.21	989	48.55	40.80	45.49	43.12	46.49	31.80
41.38	993	52.43	43.13	47.82	45.44	48.81	35.68
41.54	997	52.00	42.87	47.56	45.18	48.56	35.25
41.71	1,001	48.54	40.80	45.49	43.11	46.49	31.79
42.13	1,011	44.98	38.67	43.36	40.98	44.36	28.23
42.46	1,019	49.01	41.08	45.77	43.39	46.77	32.26
42.79	1,027	54.67	44.47	49.16	46.78	50.15	37.92
43.13	1,035	48.94	41.04	45.73	43.35	46.73	32.19
43.46	1,043	53.96	44.04	48.73	46.36	49.73	37.21

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
44.63	1,071	51.07	42.31	47.00	44.63	48.00	34.32
45.00	1,080	48.78	40.94	45.63	43.26	46.63	32.03
45.38	1,089	51.72	42.70	47.39	45.01	48.39	34.97
45.79	1,099	49.97	41.65	46.34	43.97	47.34	33.22
46.13	1,107	50.21	41.80	46.49	44.11	47.49	33.46
46.50	1,116	56.49	45.56	50.25	47.87	51.24	39.74
46.83	1,124	48.10	40.54	45.23	42.85	46.22	31.35
47.17	1,132	47.35	40.09	44.78	42.40	45.77	30.60
47.46	1,139	46.96	39.85	44.54	42.17	45.54	30.21
47.79	1,147	53.27	43.63	48.32	45.94	49.32	36.52
48.21	1,157	51.04	42.29	46.98	44.61	47.98	34.29
48.71	1,169	49.74	41.52	46.21	43.83	47.20	32.99
49.29	1,183	45.89	39.21	43.90	41.53	44.90	29.14
49.79	1,195	53.19	43.58	48.27	45.89	49.27	36.44
49.96	1,199	50.07	41.71	46.40	44.03	47.40	33.32
50.29	1,207	46.96	39.85	44.54	42.17	45.54	30.21
50.71	1,217	48.87	41.00	45.69	43.31	46.68	32.12
51.21	1,229	46.87	39.80	44.49	42.11	45.49	30.12
51.38	1,233	53.46	43.74	48.43	46.06	49.43	36.71
51.75	1,242	48.06	40.51	45.20	42.83	46.20	31.31
52.08	1,250	46.87	39.80	44.49	42.11	45.49	30.12
52.46	1,259	46.64	39.66	44.35	41.98	45.35	29.89
52.79	1,267	48.93	41.03	45.72	43.35	46.72	32.18
53.29	1,279	46.24	39.42	44.11	41.74	45.11	29.49
53.75	1,290	45.15	38.77	43.46	41.08	44.46	28.40
54.08	1,298	49.04	41.10	45.79	43.41	46.79	32.29
54.58	1,310	44.76	38.54	43.23	40.85	44.22	28.01
54.75	1,314	50.83	42.17	46.86	44.48	47.86	34.08
55.08	1,322	49.02	41.09	45.78	43.40	46.77	32.27
55.42	1,330	54.77	44.53	49.22	46.84	50.21	38.02
55.92	1,342	45.56	39.02	43.71	41.33	44.70	28.81
56.33	1,352	52.02	42.88	47.57	45.19	48.57	35.27
56.67	1,360	46.71	39.70	44.39	42.02	45.39	29.96
57.00	1,368	46.33	39.48	44.17	41.79	45.16	29.58
57.33	1,376	52.83	43.37	48.06	45.68	49.05	36.08

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
58.83	1,412	46.21	39.40	44.09	41.72	45.09	29.46
59.00	1,416	45.56	39.02	43.71	41.33	44.70	28.81
59.33	1,424	53.53	43.78	48.47	46.10	49.47	36.78
59.67	1,432	47.18	39.99	44.68	42.30	45.67	30.43
60.17	1,444	48.92	41.03	45.72	43.34	46.71	32.17
60.33	1,448	53.59	43.82	48.51	46.13	49.51	36.84
60.67	1,456	47.11	39.94	44.63	42.26	45.63	30.36
61.04	1,465	46.47	39.56	44.25	41.87	45.25	29.72
61.54	1,477	49.08	41.12	45.81	43.44	46.81	32.33
62.04	1,489	45.34	38.88	43.57	41.20	44.57	28.59
62.63	1,503	44.76	38.54	43.23	40.85	44.22	28.01
62.79	1,507	50.83	42.17	46.86	44.48	47.86	34.08
63.21	1,517	48.18	40.58	45.27	42.90	46.27	31.43
63.54	1,525	46.05	39.31	44.00	41.62	45.00	29.30
63.88	1,533	45.47	38.96	43.65	41.28	44.65	28.72
64.21	1,541	46.28	39.45	44.14	41.76	45.13	34.67
64.71	1,553	41.57	36.63	41.32	38.94	42.32	29.96
65.29	1,567	48.45	40.74	45.43	43.06	46.43	36.84
65.63	1,575	43.40	37.72	42.41	40.04	43.41	31.79
65.96	1,583	39.43	35.35	40.04	37.66	41.04	27.82
66.46	1,595	48.24	40.62	45.31	42.93	46.31	36.63
66.79	1,603	41.53	36.60	41.29	38.92	42.29	29.92
67.13	1,611	42.02	36.90	41.59	39.21	42.58	30.41
67.50	1,620	46.86	39.79	44.48	42.11	45.48	35.25
68.00	1,632	39.43	35.35	40.04	37.66	41.04	27.82
68.33	1,640	48.72	40.91	45.60	43.22	46.59	37.11
68.75	1,650	40.29	35.86	40.55	38.18	41.55	28.68
69.08	1,658	43.36	37.70	42.39	40.01	43.39	31.75
69.42	1,666	39.98	35.68	40.37	37.99	41.36	28.37
69.75	1,674	40.99	36.28	40.97	38.59	41.97	29.38
70.29	1,687	39.82	35.58	40.27	37.89	41.27	28.21
70.67	1,696	39.68	35.50	40.19	37.81	41.18	28.07
71.04	1,705	40.54	36.01	40.70	38.33	41.70	28.93
71.38	1,713	39.77	35.55	40.24	37.87	41.24	28.16
71.71	1,721	34.74	32.54	37.23	34.86	38.23	26.56

Table E.1 Temperature profiles for RUN I (continued)

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
72.71	1,745	35.83	33.20	37.89	35.51	38.88	27.65
73.21	1,757	36.86	33.81	38.50	36.13	39.50	28.68
73.83	1,772	40.56	36.03	40.72	38.34	41.71	32.38
74.33	1,784	38.27	34.66	39.35	36.97	40.34	30.09
74.83	1,796	40.19	35.80	40.49	38.12	41.49	32.01
75.33	1,808	38.14	34.58	39.27	36.89	40.27	29.96
75.50	1,812	37.16	33.99	38.68	36.31	39.68	28.98
76.00	1,824	34.92	32.66	37.35	34.97	38.34	28.46
76.33	1,832	35.57	33.04	37.73	35.36	38.73	29.11
76.67	1,840	35.44	32.97	37.66	35.28	38.65	28.98
77.00	1,848	40.17	35.80	40.49	38.11	41.48	33.71
77.33	1,856	35.19	32.82	37.51	35.13	38.50	28.73
77.67	1,864	36.15	33.39	38.08	35.70	39.08	29.69
78.00	1,872	40.90	36.23	40.92	38.55	41.92	34.44
78.50	1,884	34.27	32.27	36.96	34.58	37.95	27.81
79.04	1,897	38.71	34.92	39.61	37.24	40.61	32.25
79.54	1,909	32.72	31.34	36.03	33.65	37.03	26.26
80.04	1,921	40.05	35.72	40.41	38.04	41.41	33.59
80.38	1,929	36.71	33.73	38.42	36.04	39.41	30.25
80.75	1,938	39.57	35.44	40.13	37.75	41.12	33.11
81.33	1,952	37.90	34.44	39.13	36.75	40.13	31.44
81.83	1,964	40.31	35.88	40.57	38.19	41.57	33.85
82.33	1,976	34.27	32.27	36.96	34.58	37.95	27.81
82.83	1,988	39.54	35.42	40.11	37.73	41.11	33.08
83.33	2,000	40.16	35.79	40.48	38.10	41.48	33.70
83.92	2,014	36.85	33.81	38.50	36.12	39.50	30.39
84.50	2,028	38.44	34.76	39.45	37.08	40.45	31.98
84.83	2,036	42.96	37.47	42.16	39.78	43.15	36.50
85.17	2,044	38.73	34.94	39.63	37.25	40.62	32.27

Table E.2 Temperature profiles for RUN II

time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
-	-	27.83	28.33	27.83	27.83	27.83	28.75
0.04	1	28.46	28.46	28.19	27.95	27.95	27.76
0.21	5	29.89	28.52	29.65	28.28	29.28	25.37
0.38	9	31.04	27.80	30.67	28.05	30.42	22.31
0.54	13	32.36	28.76	31.75	28.89	31.38	23.77
0.92	22	35.66	35.30	34.33	35.06	33.96	34.53
1.08	26	36.61	34.30	35.88	34.55	35.52	28.34
1.25	30	36.85	33.32	36.48	33.56	36.24	26.40
1.42	34	37.36	33.23	36.89	33.36	36.40	25.30
1.58	38	37.70	33.08	36.61	33.45	36.12	27.32
1.75	42	37.96	35.65	36.36	35.51	36.00	34.37
1.92	46	38.92	37.34	36.97	37.22	36.73	34.38
2.08	50	40.23	37.07	38.16	37.43	37.67	31.25
2.33	56	42.41	36.70	39.01	37.31	38.89	28.83
2.54	61	44.11	36.21	39.74	37.05	39.48	27.12
2.71	65	44.32	37.87	39.94	38.36	39.70	32.35
2.88	69	44.88	39.89	40.50	40.38	40.26	35.64
3.04	73	45.27	39.56	41.38	40.04	41.14	31.88
3.29	79	45.36	37.95	41.84	38.55	41.47	27.60
3.46	83	45.22	37.20	41.82	37.93	41.46	26.55
3.79	91	44.28	40.39	41.24	40.51	41.00	35.68
3.96	95	44.15	40.75	41.84	40.85	41.46	34.48
4.13	99	44.27	39.77	42.08	40.26	41.72	31.72
4.29	103	44.31	38.84	42.36	39.08	41.76	29.66
4.46	107	44.52	38.20	42.09	38.69	41.60	28.26
4.63	111	44.09	38.74	41.78	38.99	41.30	31.46
4.88	117	43.72	41.16	41.77	41.16	41.28	36.28
5.04	121	44.24	40.83	42.17	40.95	41.81	33.82
5.54	133	44.60	37.43	41.93	37.91	41.68	28.36
5.71	137	44.22	39.84	41.42	39.84	41.18	34.89
5.88	141	44.29	41.37	41.85	41.26	41.50	37.49
6.04	145	44.48	40.71	42.29	40.83	41.92	33.34
6.21	149	44.92	38.59	42.48	39.08	42.12	27.96
6.38	153	45.00	36.97	42.22	37.74	41.97	26.01
7.04	169	44.85	40.47	42.30	40.72	41.93	35.37

Table E.2 Temperature profiles for RUN II (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
7.04	169	44.85	40.47	42.30	40.72	41.93	35.37
7.21	173	45.17	38.48	42.25	39.09	42.25	31.29
7.38	177	45.56	37.18	42.16	37.77	42.27	28.71
7.54	181	45.48	36.60	41.71	37.21	41.71	27.89
7.71	185	44.78	38.83	41.26	39.19	41.14	33.84
7.88	189	44.92	40.79	41.64	41.03	41.27	37.02
8.04	193	45.78	40.18	42.25	40.43	42.01	34.82
8.21	197	45.99	38.94	42.36	39.32	42.12	32.13
8.38	201	46.36	37.72	42.34	38.21	42.10	29.63
8.54	205	46.53	37.04	42.03	37.53	42.15	28.70
8.71	209	46.08	39.28	41.71	39.40	41.59	33.80
8.88	213	46.25	41.02	41.99	41.14	41.75	37.13
9.04	217	47.14	40.21	42.64	40.33	42.40	34.50
9.21	221	47.42	38.79	42.80	39.28	42.44	31.86
9.38	225	47.71	37.98	42.84	38.59	42.48	30.53
9.54	229	47.77	37.55	42.66	38.17	42.30	29.35
9.71	233	47.20	40.15	42.09	40.27	41.84	35.39
9.88	237	47.36	41.89	42.50	41.76	42.36	38.47
9.92	238	47.81	41.85	42.83	41.85	42.58	37.96
10.04	241	48.37	40.59	43.27	40.84	43.02	35.24
10.21	245	48.88	39.39	43.41	39.64	43.16	32.22
10.38	249	49.06	37.75	43.22	38.23	42.98	29.67
10.54	253	49.06	37.02	43.10	37.39	42.74	28.31
10.79	259	48.50	39.98	42.53	40.22	42.17	35.49
10.96	263	49.09	40.82	43.25	40.94	42.76	36.20
11.13	267	49.49	39.39	43.65	39.52	43.04	32.95
11.54	277	49.84	35.98	43.16	36.35	42.55	26.99
11.71	281	49.20	38.26	42.27	38.39	41.92	32.55
11.88	285	49.37	40.38	42.69	40.38	42.08	36.61
12.04	289	49.69	39.11	43.24	39.36	42.77	34.02
12.29	295	49.29	36.53	42.73	36.89	42.48	28.29
12.46	299	49.59	35.25	42.80	35.74	42.43	26.12
12.96	311	49.92	41.53	43.60	41.66	43.11	37.89
13.13	315	50.58	40.37	44.13	40.00	43.89	33.56
13.17	316	50.51	40.06	44.19	39.58	43.96	32.53

Table E.2 Temperature profiles for RUN II (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
13.21	317	50.46	39.88	44.25	39.27	43.89	32.10
13.42	322	50.50	38.34	44.18	37.49	43.69	29.40
13.58	326	49.98	36.73	43.54	36.50	43.07	27.37
13.83	332	49.25	39.40	42.80	39.16	42.32	34.54
14.13	339	49.32	39.35	43.62	38.76	42.89	32.80
14.38	345	49.33	37.65	43.49	36.80	42.76	28.20
14.67	352	48.70	36.76	42.72	36.16	41.88	28.55
14.92	358	48.19	39.44	42.59	39.18	41.74	35.29
15.25	366	47.94	37.72	42.83	37.36	42.10	30.52
15.50	372	47.63	36.45	42.89	35.96	41.68	27.96
15.88	381	47.08	40.61	42.95	40.03	41.24	37.96
16.42	394	47.50	39.35	43.25	37.53	42.39	30.94
16.67	400	47.02	39.84	42.53	38.40	41.68	33.29
16.92	406	47.31	41.96	43.18	41.23	42.08	39.41
17.08	410	47.74	41.29	43.72	40.32	42.87	36.56
17.25	414	47.62	40.09	43.73	39.11	42.88	33.90
17.46	419	47.46	38.70	43.81	38.22	42.84	31.27
17.71	425	47.26	39.85	43.25	39.60	42.16	34.85
18.00	432	47.38	40.35	43.63	39.62	42.45	35.00
18.04	433	47.79	39.48	44.33	38.73	42.87	32.39
18.13	435	47.64	37.18	44.01	37.56	42.66	28.84
18.33	440	47.70	36.40	43.33	36.64	42.11	28.04
18.54	445	47.33	36.02	42.71	36.51	41.73	28.16
18.71	449	46.76	35.09	42.15	35.35	41.30	27.72
18.88	453	46.66	36.20	42.04	36.32	41.06	30.57
19.17	460	46.25	34.94	41.63	35.07	40.78	27.79
19.42	466	45.63	33.35	41.26	33.49	40.05	25.92
19.67	472	44.86	33.31	40.36	33.43	39.26	25.87
19.92	478	44.34	34.98	39.96	34.98	38.87	29.32
20.21	485	44.07	33.13	39.94	33.02	38.73	26.45
20.42	490	43.90	33.08	39.52	32.96	38.43	26.26
20.63	495	43.56	33.11	39.19	33.11	38.21	26.66
20.92	502	43.25	35.71	38.99	35.71	38.02	31.81
21.33	512	45.14	37.12	42.10	37.60	40.76	30.52
21.63	519	45.98	36.74	42.70	37.23	41.36	29.14

Table E.2 Temperature profiles for RUN II (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
22.17	532	47.83	36.52	43.57	37.02	42.37	27.91
22.42	538	48.50	36.22	43.76	36.70	42.66	27.09
24.08	578	50.00	40.64	44.88	42.69	44.64	34.44
24.33	584	50.64	39.33	45.52	41.63	45.16	31.40
24.71	593	50.71	41.35	45.72	43.29	44.99	34.66
24.88	597	50.76	43.47	46.02	45.05	45.54	38.01
25.04	601	51.66	41.93	47.65	44.24	46.80	34.76
25.33	608	51.95	40.89	47.94	43.20	46.97	32.13
25.63	615	51.85	41.15	47.84	43.34	46.86	32.53
25.88	621	51.90	44.00	47.88	45.81	47.03	37.68
25.96	623	51.59	44.53	48.18	46.60	47.33	38.32
26.13	627	52.46	43.22	48.93	45.89	48.08	35.80
26.29	631	52.67	42.70	48.90	45.40	48.32	34.33
26.38	633	52.85	42.39	49.21	45.20	48.36	33.41
26.54	637	53.06	41.14	48.92	44.79	48.56	31.42
26.63	639	52.73	41.91	48.84	45.44	48.23	32.91
26.79	643	52.07	42.26	46.15	45.42	45.79	36.92
26.92	646	51.89	43.71	47.12	46.88	46.63	37.76
27.04	649	51.25	43.10	47.84	46.02	47.24	35.81
27.21	653	51.45	42.33	48.28	44.27	47.55	33.82
27.38	657	51.62	41.53	48.58	43.84	47.36	32.29
27.63	663	51.55	41.08	48.75	43.52	47.41	31.60
27.92	670	50.94	42.31	47.78	45.10	47.17	34.90
28.13	675	51.20	41.47	48.28	44.27	47.67	32.96
28.42	682	50.88	39.82	47.97	42.14	47.49	30.18
28.71	689	49.97	40.96	46.92	42.54	46.43	33.80
29.17	700	49.73	39.51	47.30	41.09	46.93	30.11
29.54	709	49.02	38.56	46.71	39.54	46.10	29.01
29.79	715	48.45	40.91	45.76	41.75	45.51	35.30
29.96	719	48.04	41.59	46.21	42.81	45.85	35.50
30.67	736	48.02	38.05	46.44	38.78	45.95	27.99
30.88	741	47.53	38.41	45.83	38.90	45.22	29.73
31.21	749	47.46	38.22	45.63	38.84	45.04	29.41
31.46	755	47.49	37.40	45.42	38.13	44.69	28.31
31.67	760	47.03	38.65	44.85	39.25	44.24	31.34

Table E.2 Temperature profiles for RUN II (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
32.17	772	47.39	38.27	45.32	38.24	44.84	29.83
32.33	776	47.50	38.02	45.19	38.87	44.59	29.32
32.79	787	47.33	40.64	44.66	41.62	44.05	35.05
33.04	793	48.07	40.04	45.51	40.89	44.91	32.63
33.33	800	48.38	38.04	45.58	39.02	45.09	29.10
33.71	809	48.16	40.02	45.00	40.75	44.40	33.33
34.63	831	49.01	39.53	45.85	40.50	45.37	31.87
34.88	837	49.62	41.23	46.46	42.56	45.97	34.91
35.13	843	49.88	40.15	46.84	40.88	46.23	32.61
35.33	848	50.20	39.26	46.80	40.19	46.19	30.84
35.79	859	49.67	41.40	46.27	42.50	45.78	35.82
36.08	866	49.68	39.35	46.64	40.32	46.28	31.81
36.50	876	49.69	37.90	46.41	38.99	45.92	29.20
36.67	880	49.49	39.76	45.96	40.73	45.23	33.20
36.83	884	49.27	41.86	46.11	42.71	45.50	36.63
37.00	888	49.61	42.08	46.70	43.05	46.10	36.00
37.29	895	49.70	39.73	47.02	40.46	46.54	31.95
37.88	909	49.61	42.56	46.57	44.03	46.22	37.70
38.25	918	49.82	39.86	47.27	40.95	47.03	31.70
38.38	921	50.06	39.00	47.26	39.98	47.03	30.46
38.79	931	49.28	41.13	46.48	42.22	45.99	36.15
39.00	936	48.96	39.47	46.65	40.70	46.42	32.93
39.33	944	49.66	38.60	46.99	39.57	46.63	30.79
39.67	952	48.92	38.10	45.89	38.83	45.52	30.92
40.13	963	48.94	38.73	46.14	39.33	46.14	31.67
40.42	970	49.05	37.38	46.38	38.35	46.14	29.79
41.13	987	48.84	40.45	46.65	41.18	46.53	34.37
41.63	999	48.77	39.29	46.23	39.66	45.98	33.10
42.42	1,018	48.91	35.90	47.70	36.51	46.12	28.40
42.58	1,022	48.95	37.27	47.24	37.64	45.79	29.91
42.83	1,028	48.43	41.50	46.85	41.62	45.64	37.61
43.08	1,034	48.84	40.71	47.88	41.07	46.67	35.10
43.46	1,043	49.11	38.41	47.77	39.14	46.68	30.97
43.83	1,052	48.37	41.92	47.63	42.16	46.17	37.78
44.42	1,066	49.76	39.57	48.93	40.30	47.35	32.16

Table E.3 Temperature profiles for RUN III

Time		Temperature					
days	hours	center	r+2	r+1	r-2	r-1	room
-	-	31.12	31.12	31.12	31.12	31.12	31.52
0.04	1	32.78	31.37	32.30	32.49	33.30	32.54
0.21	5	35.82	33.19	34.12	34.30	35.12	32.35
0.46	11	40.15	35.78	36.71	36.89	37.71	31.94
0.71	17	42.49	37.18	38.11	38.30	39.11	28.68
0.88	21	43.64	37.87	38.80	38.98	39.79	30.34
1.04	25	46.48	39.57	40.50	40.68	41.50	31.75
1.29	31	49.08	41.12	43.05	42.24	44.05	28.85
2.21	53	51.71	42.70	44.63	43.81	45.62	30.00
2.58	62	52.12	42.94	44.87	44.06	45.87	28.76
2.92	70	51.29	42.45	46.38	43.56	47.37	27.14
3.33	80	51.16	42.37	46.30	43.48	47.30	28.16
3.75	90	51.99	42.87	46.80	43.98	47.80	30.45
4.46	107	50.10	41.73	45.66	42.85	46.66	27.74
4.92	118	52.60	43.23	47.16	44.35	48.16	32.89
5.58	134	53.23	43.61	47.54	44.92	48.54	27.42
6.08	146	51.65	42.66	46.59	43.97	47.59	30.66
6.33	152	51.00	42.27	46.20	43.59	47.20	29.78
6.67	160	51.57	42.62	46.55	43.93	47.54	30.43
6.83	164	53.17	43.57	47.50	44.89	48.50	32.88
7.00	168	53.38	43.70	47.63	45.01	48.63	29.52
7.25	174	53.78	43.94	47.87	41.62	48.86	27.99
7.42	178	53.66	43.87	47.80	41.55	48.79	29.14
7.58	182	53.30	43.65	47.58	41.33	48.57	28.48
7.75	186	52.96	43.45	47.38	41.13	48.38	33.38
8.17	196	52.46	43.15	47.08	40.83	48.07	27.59
8.33	200	53.35	43.68	47.61	41.37	48.61	29.01
8.58	206	53.63	43.85	47.78	41.53	48.78	27.89
8.92	214	53.84	43.97	47.90	41.66	48.90	34.11
8.96	215	54.16	44.16	48.09	41.85	49.09	33.71
9.29	223	53.63	43.84	47.77	41.53	48.77	28.73
9.46	227	53.44	43.73	47.66	41.42	48.66	27.43
9.63	231	53.46	43.74	47.67	41.43	48.67	29.69
10.38	249	53.55	43.80	47.73	41.48	48.72	28.54
10.63	255	53.49	43.76	47.69	41.45	48.69	28.32

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
10.79	259	54.52	44.38	48.31	42.06	49.30	35.38
10.92	262	55.41	44.91	48.84	42.60	49.84	32.88
11.08	266	55.10	44.73	48.66	42.41	49.65	29.50
11.33	272	55.26	44.82	48.75	42.51	49.75	28.13
11.54	277	55.24	44.81	48.74	42.49	49.73	25.68
11.75	282	54.76	44.52	48.45	43.21	49.45	30.94
11.96	287	54.77	44.53	48.46	43.22	49.46	33.85
12.17	292	54.35	44.28	48.21	42.97	49.21	30.70
12.33	296	54.45	44.34	48.27	43.03	49.27	30.25
12.46	299	54.63	44.45	48.38	43.13	49.37	28.76
12.71	305	53.85	43.98	47.91	42.66	48.90	33.11
12.88	309	53.69	43.88	47.81	42.57	48.81	37.72
13.08	314	54.46	44.34	48.27	43.03	49.27	34.43
13.29	319	54.69	44.48	48.41	43.17	49.41	31.44
13.54	325	54.67	44.47	48.40	43.16	49.40	30.50
13.71	329	54.25	44.22	48.15	42.90	49.14	31.13
13.96	335	54.06	44.10	48.03	42.79	49.03	29.25
14.08	338	53.35	43.68	47.61	42.37	48.61	28.92
14.25	342	53.83	43.97	47.90	42.66	48.90	27.15
14.50	348	53.83	43.97	49.90	42.65	50.89	35.48
14.75	354	53.42	43.72	49.65	42.41	50.65	33.53
15.00	360	53.54	43.79	49.72	42.48	50.72	31.17
15.25	366	53.31	43.66	49.59	42.34	50.58	32.50
15.42	370	53.27	43.63	49.56	42.32	50.56	37.17
15.58	374	53.21	43.60	49.53	42.28	50.52	34.45
15.75	378	53.11	43.54	49.47	42.22	50.47	32.35
16.13	387	53.53	43.79	49.72	42.47	50.72	38.86
16.25	390	53.52	43.78	49.71	42.47	50.71	35.13
16.50	396	53.63	43.85	49.78	42.53	50.77	32.26
16.67	400	53.55	43.80	49.73	42.48	50.72	31.43
16.83	404	53.46	43.75	49.68	42.43	50.67	37.92
17.00	408	52.67	43.27	49.20	41.96	50.20	33.42
17.29	415	52.03	42.89	48.82	41.58	49.82	31.07
17.67	424	51.97	42.85	46.78	41.54	47.78	35.73
17.92	430	51.72	42.71	46.64	41.39	47.63	31.82

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
18.25	438	53.63	43.85	47.78	42.53	48.78	32.41
18.38	441	53.43	43.73	47.66	42.41	48.65	37.12
18.54	445	53.40	43.71	47.64	42.40	48.64	38.73
18.79	451	53.33	43.67	49.60	42.35	50.59	31.96
18.96	455	53.27	43.63	49.56	42.32	50.56	30.07
19.21	461	53.50	43.77	49.70	42.46	50.70	35.57
19.38	465	53.31	43.65	49.58	42.34	50.58	35.74
19.58	470	53.55	43.80	49.73	42.49	50.73	32.57
19.75	474	53.53	43.79	49.72	45.10	50.72	31.09
19.92	478	53.01	43.47	49.40	44.79	50.40	34.37
20.17	484	53.03	43.49	49.42	44.80	50.41	33.46
20.38	489	53.18	43.57	49.50	44.89	50.50	32.47
20.83	500	53.36	43.68	51.37	45.00	52.37	32.12
20.92	502	53.38	43.70	51.39	45.01	52.38	31.93
21.13	507	52.99	43.46	51.15	44.78	52.15	29.67
21.29	511	53.07	43.51	51.20	44.83	52.20	30.44
21.58	518	52.22	43.00	50.69	44.32	51.69	30.71
21.75	522	51.61	42.64	50.33	43.95	51.32	36.43
22.00	528	53.10	43.53	51.22	44.84	52.22	33.16
22.25	534	52.46	43.15	50.84	44.46	51.83	34.29
22.46	539	51.22	42.41	50.10	43.72	51.09	32.75
22.71	545	50.02	41.69	49.38	43.00	50.37	33.25
22.96	551	49.08	41.13	48.82	42.44	49.81	38.35
23.17	556	49.09	41.13	48.82	42.44	49.82	28.03
23.38	561	49.09	41.13	48.82	42.45	49.82	29.00
23.54	565	49.11	41.14	48.83	42.45	49.83	30.17
23.71	569	49.24	41.22	48.91	42.53	49.91	36.13
23.88	573	48.77	40.94	48.63	42.25	49.63	35.28
24.08	578	46.73	39.72	47.41	41.03	48.41	32.30
24.25	582	45.77	39.14	46.83	40.46	47.83	31.07
24.46	587	45.02	38.70	46.39	40.01	47.38	30.17
24.63	591	45.73	39.12	46.81	40.43	47.81	35.65
24.83	596	47.99	40.48	48.17	41.79	49.16	30.86
25.25	606	47.25	40.03	47.72	42.35	48.72	30.12
25.42	610	50.84	42.18	49.87	44.49	50.87	36.71

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
25.83	620	48.34	40.68	46.37	43.00	47.37	31.21
26.00	624	46.94	39.85	45.54	42.16	46.53	29.81
26.17	628	48.75	40.93	46.62	43.24	47.62	31.62
26.33	632	50.13	41.76	47.45	44.07	48.44	36.00
26.50	636	47.02	39.89	45.58	42.21	46.58	29.89
26.75	642	48.06	40.52	46.21	42.83	47.20	30.93
26.83	644	49.31	41.26	46.95	43.58	47.95	32.18
27.00	648	47.53	40.20	45.89	42.51	46.89	30.40
27.17	652	45.82	39.18	44.87	41.49	45.86	28.69
27.33	656	46.62	39.66	45.35	41.97	46.34	29.49
27.42	658	50.52	41.99	47.68	44.30	48.68	33.39
27.58	662	48.51	40.79	46.48	43.10	47.47	31.38
27.75	666	45.73	39.12	44.81	41.44	45.81	28.60
27.92	670	43.20	37.61	43.30	39.92	44.30	26.07
28.08	674	47.51	40.19	45.88	42.50	46.88	30.38
28.21	677	52.52	43.19	48.88	45.50	49.87	35.39
28.38	681	47.20	40.00	45.69	42.32	46.69	30.07
28.54	685	44.68	38.49	44.18	40.81	45.18	27.55
28.71	689	48.09	40.54	46.23	42.85	47.22	30.96
28.92	694	51.08	42.32	48.01	44.64	49.01	33.95
29.08	698	49.63	41.46	47.15	43.77	48.14	32.50
29.29	703	51.15	42.37	48.06	44.68	49.05	34.02
29.50	708	48.59	40.83	46.52	43.15	47.52	31.46
29.67	712	46.71	39.71	45.40	42.02	46.40	29.58
29.88	717	45.85	39.19	44.88	41.51	45.88	28.72
30.08	722	48.93	41.04	46.73	43.35	47.72	31.80
30.29	727	50.91	42.22	47.91	44.54	48.91	36.78
30.54	733	49.75	41.53	47.22	43.84	48.22	32.62
30.79	739	46.04	39.31	45.00	41.62	46.00	28.91
30.96	743	44.92	38.64	44.33	40.95	45.33	27.79
31.08	746	48.08	40.53	46.22	42.84	47.22	30.95
31.29	751	50.97	42.26	47.95	44.57	48.95	36.84
31.54	757	47.45	40.15	47.84	42.47	48.84	33.32
31.79	763	46.13	39.36	47.05	41.68	48.05	29.00
32.21	773	48.20	40.60	48.29	42.91	49.29	34.07

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
32.54	781	50.15	41.77	49.46	44.08	50.45	38.02
32.75	786	46.71	39.71	45.40	42.02	46.40	29.58
32.96	791	45.85	39.19	44.88	41.51	45.88	28.72
33.13	795	47.54	40.21	45.90	42.52	46.89	30.41
33.33	800	49.81	41.56	47.25	43.88	48.25	35.68
33.46	803	49.40	41.32	47.01	43.63	48.01	35.27
33.67	808	48.92	41.03	46.72	43.35	47.72	31.79
33.88	813	46.04	39.31	45.00	41.62	46.00	28.91
34.08	818	45.36	38.90	44.59	41.22	45.59	28.23
34.25	822	48.20	40.60	46.29	42.91	47.29	34.07
34.50	828	47.69	40.30	45.99	42.61	46.98	30.56
34.67	832	46.52	39.60	45.29	41.91	46.28	29.39
34.83	836	49.89	41.61	47.30	43.93	48.30	32.76
35.00	840	45.59	39.04	44.73	41.35	45.73	31.46
35.17	844	45.81	39.17	44.86	41.48	45.86	28.68
35.42	850	48.52	40.79	46.48	43.11	47.48	31.39
35.67	856	48.10	40.54	46.23	42.85	47.23	30.97
35.83	860	45.53	39.00	44.69	41.32	45.69	28.40
36.00	864	43.54	37.81	43.50	40.13	44.50	26.41
36.17	868	49.42	41.33	47.02	43.64	48.02	32.29
36.33	872	48.19	40.59	46.28	42.91	47.28	31.06
36.50	876	45.83	39.18	44.87	41.50	45.87	28.70
36.58	878	44.68	38.49	44.18	40.81	45.18	27.55
36.75	882	48.09	40.54	46.23	42.85	47.22	30.96
36.92	886	48.94	41.04	46.73	43.36	47.73	34.81
37.04	889	49.63	41.46	47.15	43.77	48.14	32.50
37.29	895	49.40	41.32	47.01	43.63	48.01	32.27
37.46	899	50.51	41.98	48.67	44.30	49.67	38.38
37.63	903	47.27	40.04	46.73	42.36	47.73	30.14
37.79	907	47.02	39.89	46.58	42.21	47.58	29.89
37.96	911	46.21	39.41	46.10	41.72	47.10	29.08
38.13	915	48.93	41.04	47.73	43.35	48.72	31.80
38.29	919	49.81	41.56	48.25	43.88	49.25	35.68
38.46	923	49.38	41.31	48.00	43.62	48.99	35.25
38.79	931	46.13	39.36	46.05	41.68	47.05	29.00

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
39.04	937	45.36	38.90	45.59	41.22	46.59	28.23
39.21	941	48.20	40.60	47.29	42.91	48.29	34.07
39.38	945	50.91	42.22	48.91	44.54	49.91	36.78
39.54	949	48.26	40.64	47.33	42.95	48.32	34.13
39.71	953	47.56	40.22	46.91	42.53	47.90	30.43
39.88	957	46.04	39.31	46.00	41.62	47.00	28.91
40.04	961	44.92	38.64	45.33	40.95	46.33	27.79
40.21	965	49.30	41.26	47.95	43.57	48.95	32.17
40.38	969	50.97	42.26	48.95	44.57	49.95	36.84
40.54	973	50.51	41.98	48.67	44.30	49.67	38.38
40.71	977	46.89	39.81	46.50	42.13	47.50	30.14
40.88	981	46.64	39.66	44.35	41.98	45.35	29.89
40.96	983	46.31	39.46	44.15	41.78	45.15	29.56
41.21	989	48.55	40.80	45.49	43.12	46.49	31.80
41.38	993	50.43	41.93	46.62	44.24	47.62	35.68
41.46	995	50.83	42.17	46.86	44.48	47.86	36.08
41.63	999	50.07	41.71	46.40	44.03	47.40	33.32
41.88	1,005	45.75	39.13	43.82	41.44	44.82	29.00
42.04	1,009	44.57	38.42	43.11	40.74	44.11	27.82
42.21	1,013	47.70	40.30	44.99	42.61	45.98	30.95
42.38	1,017	49.86	41.59	46.28	43.90	47.28	37.11
42.54	1,021	47.72	40.31	45.00	42.62	46.00	30.97
42.71	1,025	49.49	41.37	46.06	43.68	47.05	34.74
42.88	1,029	51.87	42.79	47.48	45.10	48.48	35.12
43.04	1,033	49.40	41.31	46.00	43.63	47.00	32.65
43.29	1,039	48.09	40.53	45.22	42.84	46.22	31.34
43.38	1,041	47.22	40.01	44.70	42.32	45.70	34.58
43.54	1,045	50.59	42.03	46.72	44.34	47.71	37.95
43.71	1,049	46.65	39.67	44.36	41.98	45.36	34.01
43.96	1,055	47.67	40.28	44.97	42.59	45.97	30.92
44.13	1,059	48.43	40.73	45.42	43.05	46.42	31.68
44.29	1,063	48.90	41.01	45.70	43.33	46.70	36.26
44.63	1,071	46.96	39.85	44.54	42.17	45.54	34.32
44.79	1,075	48.64	40.86	45.55	43.17	46.55	31.89
44.96	1,079	47.38	40.10	44.79	42.42	45.79	30.63

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
45.29	1,087	46.96	39.85	44.54	42.17	45.54	34.32
45.46	1,091	45.96	39.26	43.95	41.57	44.94	33.32
45.63	1,095	44.61	38.45	43.14	40.76	44.13	31.97
45.83	1,100	49.21	41.20	45.89	43.51	46.89	34.60
46.00	1,104	49.63	41.45	46.14	43.76	47.14	35.02
46.13	1,107	48.07	40.52	45.21	42.83	46.20	33.46
46.38	1,113	48.77	40.94	45.63	43.25	46.62	34.16
46.63	1,119	48.07	40.52	45.21	42.83	46.20	35.11
46.79	1,123	48.87	41.00	45.69	43.31	46.68	32.12
46.96	1,127	47.27	40.04	44.73	42.35	45.73	34.31
47.13	1,131	47.59	40.23	44.92	42.54	45.92	30.84
47.29	1,135	47.26	40.03	44.72	42.35	45.72	30.51
47.38	1,137	47.30	40.06	44.75	42.37	45.74	30.55
47.54	1,141	47.46	40.15	44.84	42.47	45.84	30.71
47.71	1,145	49.39	41.31	46.00	43.62	46.99	36.43
47.88	1,149	47.69	40.29	44.98	42.60	45.98	34.73
48.04	1,153	48.47	40.76	45.45	43.07	46.44	31.72
48.21	1,157	47.25	40.03	44.72	42.34	45.71	34.29
48.38	1,161	49.02	41.09	45.78	43.40	46.77	32.27
48.54	1,165	47.66	40.27	44.96	42.59	45.96	30.91
48.71	1,169	49.74	41.52	46.21	43.83	47.20	32.99
48.88	1,173	50.35	41.88	46.57	44.20	47.57	37.39
49.04	1,177	45.06	38.72	43.41	41.03	44.40	28.31
49.21	1,181	44.77	38.54	43.23	40.86	44.23	28.02
49.38	1,185	45.39	38.91	43.60	41.23	44.60	28.64
49.54	1,189	48.71	40.90	45.59	43.21	46.59	31.96
49.71	1,193	50.17	41.77	46.46	44.09	47.46	37.21
49.88	1,197	47.62	40.25	44.94	42.56	45.94	34.66
50.04	1,201	49.05	41.10	45.79	43.42	46.79	32.30
50.17	1,204	47.69	40.29	44.98	42.60	45.98	30.94
50.33	1,208	46.52	39.59	44.28	41.90	45.28	29.77
50.50	1,212	49.16	41.17	45.86	43.48	46.86	32.41
50.67	1,216	48.99	41.07	45.76	43.38	46.76	36.03
50.88	1,221	47.14	39.96	44.65	42.27	45.65	30.39
51.13	1,227	47.71	40.30	44.99	42.62	45.99	30.96

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
51.46	1,235	48.31	40.66	45.35	42.97	46.35	35.35
51.63	1,239	46.36	39.49	44.18	41.81	45.18	29.61
51.83	1,244	48.16	40.57	45.26	42.89	46.26	31.41
51.96	1,247	46.56	39.61	44.30	41.93	45.30	29.81
52.13	1,251	48.37	40.70	45.39	43.01	46.38	31.62
52.25	1,254	47.46	40.15	44.84	42.47	45.84	34.50
52.33	1,256	48.82	40.97	45.66	43.28	46.65	32.07
52.54	1,261	48.08	40.52	45.21	42.84	46.21	31.33
52.67	1,264	47.58	40.22	44.91	42.54	45.91	30.83
52.83	1,268	46.45	39.55	44.24	41.86	45.24	33.49
52.96	1,271	47.15	39.97	44.66	42.28	45.65	30.40
53.13	1,275	45.44	38.94	43.63	41.26	44.63	28.69
53.38	1,281	46.35	39.49	44.18	41.80	45.18	33.39
53.58	1,286	47.72	40.31	45.00	42.62	46.00	30.97
53.75	1,290	45.15	38.77	43.46	41.08	44.46	28.40
53.92	1,294	43.16	37.58	42.27	39.89	43.27	26.41
54.08	1,298	49.04	41.10	45.79	43.41	46.79	32.29
54.25	1,302	47.81	40.36	45.05	42.68	46.05	31.06
54.42	1,306	45.45	38.95	43.64	41.26	44.64	28.70
54.58	1,310	44.76	38.54	43.23	40.85	44.22	28.01
54.75	1,314	47.04	39.90	44.59	42.21	45.59	34.08
54.92	1,318	46.42	39.53	44.22	41.84	45.22	33.46
55.00	1,320	45.68	39.09	43.78	41.40	44.77	32.72
55.13	1,323	49.41	41.32	46.01	43.63	47.01	32.66
55.29	1,327	47.38	40.10	44.79	42.42	45.79	34.42
55.46	1,331	48.21	40.60	45.29	42.91	46.29	31.46
55.63	1,335	46.33	39.48	44.17	41.79	45.16	29.58
55.79	1,339	46.31	39.46	44.15	41.78	45.15	29.56
55.96	1,343	45.93	39.24	43.93	41.55	44.92	29.18
56.13	1,347	46.59	39.63	44.32	41.95	45.32	33.63
56.29	1,351	49.04	41.10	45.79	43.41	46.79	36.08
56.50	1,356	45.58	39.03	43.72	41.34	44.71	32.62
56.71	1,361	45.75	39.13	43.82	41.44	44.82	29.00
56.83	1,364	44.78	38.55	43.24	40.86	44.24	28.03
57.21	1,373	50.07	41.71	46.40	44.03	47.40	37.11

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
57.50	1,380	46.28	39.45	44.14	41.76	45.13	33.32
57.67	1,384	43.00	37.48	42.17	39.80	43.17	30.04
57.83	1,388	45.17	38.78	43.47	41.10	44.47	28.42
58.04	1,393	46.33	39.48	44.17	41.79	45.16	29.58
58.21	1,397	48.16	40.57	45.26	42.89	46.26	35.20
58.42	1,402	49.59	41.43	46.12	43.74	47.11	36.63
58.71	1,409	46.33	39.48	44.17	41.79	45.16	29.58
58.75	1,410	46.67	39.68	44.37	41.99	45.37	29.92
58.96	1,415	45.83	39.18	43.87	41.49	44.86	29.08
59.13	1,419	48.55	40.80	45.49	43.12	46.49	31.80
59.29	1,423	48.64	40.86	45.55	43.17	46.55	35.68
59.46	1,427	48.21	40.60	45.29	42.91	46.29	35.25
59.67	1,432	47.18	39.99	44.68	42.30	45.67	30.43
59.88	1,437	45.17	38.78	43.47	41.10	44.47	28.42
60.04	1,441	44.98	38.67	43.36	40.98	44.36	28.23
60.25	1,446	48.16	40.57	45.26	42.89	46.26	35.20
60.46	1,451	47.31	40.06	44.75	42.38	45.75	30.56
60.63	1,455	46.14	39.36	44.05	41.68	45.05	29.39
60.79	1,459	45.72	39.11	43.80	41.43	44.80	32.76
60.96	1,463	44.42	38.33	43.02	40.65	44.02	31.46
61.13	1,467	45.43	38.94	43.63	41.25	44.63	28.68
61.29	1,471	44.12	38.15	42.84	40.47	43.84	27.37
61.46	1,475	46.83	39.78	44.47	42.09	45.46	33.87
61.67	1,480	42.98	37.47	42.16	39.79	43.16	30.02
61.83	1,484	41.46	36.56	41.25	38.88	42.25	28.50
62.00	1,488	39.40	35.33	40.02	37.64	41.02	26.44
62.13	1,491	45.25	38.83	43.52	41.14	44.52	32.29
62.29	1,495	44.02	38.09	42.78	40.41	43.78	31.06
62.46	1,499	41.66	36.68	41.37	39.00	42.37	28.70
62.71	1,505	43.92	38.03	42.72	40.35	43.72	30.96
63.00	1,512	45.46	38.96	43.65	41.27	44.64	32.50
63.21	1,517	44.39	38.32	43.01	40.63	44.00	31.43
63.46	1,523	50.98	42.26	46.95	44.57	47.95	38.02
63.71	1,529	42.88	37.41	42.10	39.73	43.10	29.92
64.04	1,537	43.37	37.71	42.40	40.02	43.39	30.41

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
64.38	1,545	48.23	40.61	45.30	42.93	46.30	35.27
64.63	1,551	43.39	37.72	42.41	40.03	43.40	30.43
64.79	1,555	41.87	36.81	41.50	39.12	42.50	28.91
64.96	1,559	40.75	36.14	40.83	38.45	41.83	27.79
65.13	1,563	45.13	38.76	43.45	41.07	44.45	32.17
65.29	1,567	49.80	41.55	46.24	43.87	47.24	36.84
65.46	1,571	48.21	40.60	45.29	42.91	46.29	35.25
65.71	1,577	43.00	37.48	42.17	39.80	43.17	30.04
65.88	1,581	41.38	36.52	41.21	38.83	42.20	28.42
66.04	1,585	41.19	36.40	41.09	38.71	42.09	28.23
66.21	1,589	47.03	39.90	44.59	42.21	45.58	34.07
66.38	1,593	46.98	39.87	44.56	42.18	45.55	34.02
66.54	1,597	50.98	42.26	46.95	44.57	47.95	38.02
66.71	1,601	42.22	37.02	41.71	39.33	42.70	29.26
66.88	1,605	42.42	37.14	41.83	39.45	42.82	29.46
67.04	1,609	41.77	36.75	41.44	39.06	42.44	28.81
67.25	1,614	46.59	39.63	44.32	41.95	45.32	33.63
67.46	1,619	48.23	40.61	45.30	42.93	46.30	35.27
67.63	1,623	45.58	39.03	43.72	41.34	44.71	32.62
67.79	1,627	42.92	37.44	42.13	39.75	43.12	29.96
68.00	1,632	40.78	36.16	40.85	38.47	41.84	27.82
68.08	1,634	41.19	36.40	41.09	38.71	42.09	28.23
68.25	1,638	47.03	39.90	44.59	42.21	45.58	34.07
68.42	1,642	43.99	38.08	42.77	40.39	43.76	31.03
68.58	1,646	43.59	37.84	42.53	40.15	43.52	30.63
68.75	1,650	41.64	36.67	41.36	38.98	42.36	28.68
68.92	1,654	43.30	37.66	42.35	39.98	43.35	30.34
69.08	1,658	44.71	38.51	43.20	40.82	44.19	31.75
69.25	1,662	41.92	36.84	41.53	39.15	42.53	28.96
69.42	1,666	41.33	36.49	41.18	38.80	42.17	28.37
69.58	1,670	40.32	35.88	40.57	38.19	41.57	27.36
69.75	1,674	42.34	37.09	41.78	39.40	42.78	29.38
69.92	1,678	47.27	40.04	44.73	42.35	45.73	34.31
70.08	1,682	47.66	40.27	44.96	42.59	45.96	34.70
70.50	1,692	41.60	36.65	41.34	38.96	42.33	28.64

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
70.88	1,701	38.31	34.68	39.37	36.99	40.37	25.35
71.04	1,705	41.89	36.82	41.51	39.13	42.51	28.93
71.13	1,707	41.64	36.67	41.36	38.98	42.36	28.68
71.38	1,713	41.12	36.36	41.05	38.67	42.05	28.16
71.54	1,717	40.12	35.76	40.45	38.07	41.45	27.16
71.71	1,721	39.52	35.40	40.09	37.72	41.09	26.56
71.88	1,725	44.08	38.13	42.82	40.44	43.82	31.12
72.04	1,729	43.27	37.65	42.34	39.96	43.33	30.31
72.21	1,733	41.74	36.73	41.42	39.04	42.42	28.78
72.46	1,739	40.68	36.10	40.79	38.41	41.78	27.72
72.58	1,742	40.29	35.86	40.55	38.18	41.55	27.33
72.75	1,746	41.83	36.78	41.47	39.10	42.47	28.87
72.92	1,750	44.94	38.65	43.34	40.96	44.33	31.98
73.08	1,754	42.47	37.17	41.86	39.48	42.85	29.51
73.29	1,759	41.09	36.34	41.03	38.66	42.03	28.13
73.42	1,762	41.34	36.49	41.18	38.80	42.18	28.38
73.63	1,767	40.38	35.92	40.61	38.23	41.60	27.42
73.79	1,771	44.26	38.24	42.93	40.55	43.93	31.30
73.96	1,775	46.01	39.29	43.98	41.60	44.97	33.05
74.13	1,779	43.62	37.86	42.55	40.17	43.54	30.66
74.29	1,783	43.58	37.83	42.52	40.14	43.52	30.62
74.46	1,787	42.19	37.00	41.69	39.31	42.69	29.23
74.63	1,791	41.85	36.80	41.49	39.11	42.48	28.89
74.75	1,794	45.11	38.75	43.44	41.06	44.43	32.15
74.83	1,796	44.97	38.66	43.35	40.98	44.35	32.01
75.00	1,800	43.14	37.57	42.26	39.88	43.26	30.18
75.17	1,804	42.02	36.90	41.59	39.21	42.59	29.06
75.33	1,808	42.92	37.44	42.13	39.75	43.12	29.96
75.46	1,811	42.10	36.95	41.64	39.26	42.63	29.14
75.67	1,816	41.78	36.75	41.44	39.07	42.44	28.82
75.83	1,820	44.56	38.42	43.11	40.73	44.10	31.60
76.00	1,824	41.42	36.54	41.23	38.85	42.23	28.46
76.33	1,832	42.07	36.93	41.62	39.24	42.61	29.11
76.50	1,836	41.68	36.69	41.38	39.01	42.38	28.72
76.83	1,844	45.77	39.14	43.83	41.46	44.83	32.81

Table E.3 Temperature profiles for RUN III (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
77.13	1,851	44.72	38.51	43.20	40.83	44.20	31.76
77.29	1,855	41.99	36.88	41.57	39.19	42.57	29.03
77.46	1,859	40.26	35.85	40.54	38.16	41.53	27.30
77.58	1,862	39.94	35.65	40.34	37.97	41.34	26.98
77.75	1,866	43.04	37.51	42.20	39.82	43.20	30.08
77.92	1,870	47.17	39.98	44.67	42.29	45.67	34.21
78.08	1,874	46.43	39.54	44.23	41.85	45.22	33.47
78.29	1,879	41.36	36.50	41.19	38.82	42.19	28.40
78.50	1,884	40.77	36.15	40.84	38.46	41.84	27.81
78.67	1,888	41.28	36.46	41.15	38.77	42.14	28.32
78.88	1,893	48.46	40.75	45.44	43.06	46.44	35.50
79.04	1,897	45.21	38.81	43.50	41.12	44.49	32.25
79.29	1,903	41.96	36.86	41.55	39.18	42.55	29.00
79.46	1,907	39.72	35.52	40.21	37.84	41.21	26.76
79.63	1,911	38.83	34.99	39.68	37.30	40.68	25.87
79.79	1,915	43.90	38.02	42.71	40.34	43.71	30.94
79.96	1,919	47.80	40.36	45.05	42.67	46.04	34.84
80.13	1,923	44.84	38.59	43.28	40.90	44.27	31.88
80.33	1,928	43.77	37.95	42.64	40.26	43.63	30.81
80.46	1,931	42.13	36.96	41.65	39.28	42.65	29.17
80.63	1,935	41.30	36.47	41.16	38.78	42.15	28.34
80.75	1,938	46.07	39.32	44.01	41.63	45.01	33.11
80.92	1,942	44.18	38.20	42.89	40.51	43.88	37.72
81.13	1,947	40.89	36.23	40.92	38.54	41.91	34.43
81.79	1,963	40.17	35.80	40.49	38.11	41.48	33.71
81.96	1,967	36.18	33.41	38.10	35.72	39.10	29.72
83.46	2,003	43.63	37.87	42.56	40.18	43.55	37.17
83.71	2,009	39.26	35.25	39.94	37.57	40.94	32.80
83.88	2,013	37.51	34.21	38.90	36.52	39.89	31.05
84.04	2,017	38.13	34.58	39.27	36.89	40.26	31.67
84.25	2,022	41.06	36.33	41.02	38.64	42.02	34.60
84.58	2,030	37.82	34.39	39.08	36.70	40.08	31.36
84.75	2,034	38.71	34.92	39.61	37.24	40.61	32.25
84.92	2,038	42.06	36.93	41.62	39.24	42.61	35.60
85.04	2,041	39.88	35.62	40.31	37.94	41.31	33.42

Table E.4 Temperature profiles for RUN IV

Time		Temperature					
days	hours	center	r+2	r+1	r-2	r-1	room
-	-	27.48	27.48	27.48	27.48	27.48	27.12
0.04	1	25.75	26.36	26.12	25.99	30.96	27.48
0.46	11	36.86	33.82	36.50	33.09	37.71	27.97
0.67	16	39.80	35.18	38.71	37.13	40.05	29.35
1.13	27	44.71	39.48	43.01	39.73	44.71	27.11
1.38	33	44.61	39.14	43.76	38.29	45.83	25.50
1.71	41	43.87	39.25	42.90	38.28	44.36	29.05
1.92	46	43.60	40.20	42.63	39.23	44.09	29.05
2.21	53	43.24	38.97	42.13	38.01	42.74	25.08
2.38	57	42.95	39.05	41.85	37.85	42.82	25.39
2.54	61	42.62	39.20	41.39	38.12	42.12	25.92
2.83	68	42.66	40.35	41.08	40.35	41.69	31.85
3.38	81	43.64	41.69	41.57	40.60	38.65	27.98
3.67	88	44.30	41.50	41.99	40.17	37.98	25.37
4.00	96	44.39	40.74	41.97	38.92	38.20	24.41
4.17	100	44.31	40.67	42.13	39.08	38.48	25.15
5.21	125	46.48	42.47	43.80	41.13	40.16	25.72
5.38	129	47.11	42.48	44.44	40.79	39.93	25.00
5.67	136	47.66	42.93	44.88	41.84	40.74	28.94
5.92	142	49.06	45.17	45.66	45.42	42.50	32.05
6.50	156	50.46	45.11	47.30	42.44	43.05	27.35
7.00	168	52.25	47.49	48.21	44.93	44.45	31.93
7.17	172	52.38	46.54	48.36	43.87	44.72	30.19
7.71	185	53.24	45.95	47.65	44.49	44.73	33.98
8.21	197	56.87	47.87	49.33	45.68	46.54	31.99
8.54	205	56.87	46.67	49.69	43.37	47.40	29.57
8.92	214	57.99	49.85	50.46	48.51	49.00	36.25
8.96	215	58.50	49.99	50.96	48.41	48.78	35.34
9.04	217	58.81	50.06	51.27	47.87	48.84	34.40
9.13	219	58.83	49.83	51.53	47.28	48.98	33.25
9.17	220	58.90	49.66	51.73	47.11	49.54	32.74
9.21	221	58.87	49.51	51.94	46.71	49.14	32.33
11.25	270	57.65	46.95	53.03	42.57	51.08	28.14
11.33	272	57.39	47.06	52.89	42.32	50.34	27.71
11.50	276	57.10	46.54	52.85	41.78	50.91	27.92

Table E.4 Temperature profiles for RUN IV (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
15.54	373	54.82	45.21	54.94	41.08	51.67	29.26
15.71	377	54.81	46.42	54.68	43.62	52.25	32.58
15.96	383	55.90	47.26	55.29	44.22	52.86	30.12
16.25	390	55.50	46.14	55.75	42.01	53.06	29.78
16.50	396	54.75	45.39	55.48	40.77	52.81	29.38
16.67	400	54.35	45.82	55.19	42.92	51.90	32.01
16.79	403	54.57	46.41	54.92	43.62	52.24	31.95
17.04	409	55.11	46.12	55.84	42.96	52.68	28.46
17.25	414	54.58	45.46	55.79	41.69	52.75	29.59
17.46	419	54.00	45.00	55.34	40.75	52.79	28.48
17.71	425	53.66	46.00	55.00	43.33	52.20	32.66
18.00	432	54.48	45.97	55.70	42.45	52.90	27.12
18.25	438	53.64	44.28	55.58	40.27	53.03	28.83
18.46	443	53.01	44.26	55.32	39.76	52.65	27.89
18.71	449	52.77	45.48	54.84	42.93	52.53	33.04
18.96	455	54.34	47.16	55.55	44.73	53.97	31.76
19.21	461	54.33	46.32	56.16	42.41	54.46	28.06
19.38	465	53.77	45.38	56.08	41.24	53.40	27.53
19.63	471	52.91	45.42	55.57	41.97	53.50	31.61
19.88	477	54.18	47.61	56.00	45.31	53.81	34.06
20.08	482	54.68	47.14	56.75	43.37	54.30	29.06
20.21	485	54.06	46.40	56.74	42.02	54.18	27.59
20.38	489	53.29	44.90	56.57	40.16	54.39	28.79
20.54	493	52.12	43.48	56.00	39.48	53.20	29.59
20.71	497	51.90	45.46	55.19	42.30	53.61	35.50
20.88	501	52.71	46.39	55.51	43.47	53.32	32.25
21.04	505	52.26	44.00	55.31	40.22	53.00	28.93
21.25	510	51.79	44.37	55.44	40.12	53.61	27.39
21.46	515	51.00	42.73	55.14	38.36	53.43	25.87
21.71	521	49.76	42.47	54.02	38.70	51.95	32.97
21.96	527	50.67	43.51	54.08	40.09	52.51	31.88
22.13	531	50.15	42.98	54.04	39.45	53.31	30.61
22.46	539	49.84	42.54	54.09	38.16	53.00	28.34
22.54	541	49.44	42.39	54.06	38.38	52.72	30.82
22.71	545	50.14	44.18	53.54	41.63	53.54	36.64

Table E.4 Temperature profiles for RUN IV (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
23.08	554	52.49	46.16	55.53	42.64	54.55	32.89
23.25	558	51.29	45.06	55.76	41.29	55.28	31.56
23.46	563	51.13	43.96	55.51	39.82	54.17	30.50
23.67	568	50.70	43.53	55.56	40.00	53.50	33.71
24.38	585	48.07	40.55	53.30	36.40	51.12	27.81
24.63	591	46.73	41.51	52.08	37.86	50.38	33.40
24.71	593	47.20	42.58	52.06	39.66	49.99	35.48
25.00	600	49.58	44.60	53.35	41.56	51.28	34.15
25.17	604	49.49	44.15	53.63	40.50	52.66	32.47
25.42	610	49.06	43.00	53.93	38.85	53.21	30.29
25.67	616	48.41	43.30	53.27	40.14	52.30	36.05
26.13	627	50.81	45.70	54.70	42.42	53.12	34.45
26.38	633	49.73	44.14	54.96	40.13	53.01	31.05
26.67	640	48.20	43.10	53.55	39.94	52.10	36.79
27.08	650	49.69	44.34	54.55	40.94	52.97	35.13
27.25	654	48.97	44.35	54.44	40.46	52.01	32.60
27.42	658	48.14	43.40	54.10	39.15	52.04	30.97
27.58	662	47.10	42.59	53.42	38.83	50.98	34.74
28.08	674	48.98	45.21	53.96	41.56	52.02	35.12
28.25	678	48.20	43.82	54.04	39.94	52.33	32.65
28.42	682	47.38	42.88	53.70	38.75	51.03	31.37
28.75	690	47.00	43.71	52.47	41.16	49.67	37.95
28.96	695	48.00	44.72	52.99	42.29	50.55	35.73
29.21	701	47.66	43.89	53.49	39.88	50.82	31.82
29.46	707	46.12	42.11	52.93	37.98	50.14	31.68
29.71	713	46.15	43.22	51.98	40.80	49.05	37.90
30.08	722	47.85	44.45	53.44	41.28	50.78	34.32
30.33	728	46.60	42.59	53.53	39.06	50.98	31.11
30.42	730	46.22	42.58	53.28	38.44	51.46	30.63
30.58	734	45.13	41.35	52.54	38.20	50.47	33.80
31.08	746	47.44	44.17	53.41	41.12	50.49	35.74
31.33	752	45.94	41.93	53.24	38.77	50.32	33.12
31.58	758	44.31	41.02	51.84	37.75	49.65	34.60
32.29	775	46.54	43.62	53.47	39.98	50.80	33.46
32.54	781	44.63	41.71	52.41	37.94	50.22	34.16

Table E.4 Temperature profiles for RUN IV (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
33.54	805	44.49	42.06	52.27	38.17	49.35	34.31
34.21	821	45.78	41.17	53.45	38.12	51.62	30.84
34.42	826	42.94	39.42	51.33	35.89	49.02	30.78
34.58	830	41.39	37.85	49.89	34.58	47.70	29.65
34.75	834	41.49	39.17	48.29	36.75	45.86	35.49
34.92	838	42.72	40.90	48.43	38.71	46.37	35.24
35.13	843	42.42	39.99	48.74	36.83	46.19	31.72
36.21	869	44.06	41.15	50.14	38.47	48.08	33.29
36.38	873	43.20	40.29	49.89	37.37	48.12	31.73
36.54	877	42.24	39.32	49.53	36.28	48.20	32.46
37.67	904	43.36	42.03	49.32	40.45	47.86	37.39
38.17	916	40.65	37.00	47.58	34.57	50.86	28.03
38.42	922	38.46	35.30	45.39	32.99	48.55	28.64
38.50	924	37.95	34.91	44.88	32.60	47.92	28.99
38.75	930	39.54	38.31	43.80	37.23	46.46	37.21
38.83	932	40.75	39.63	44.39	38.44	46.93	36.44
39.00	936	41.16	39.21	45.53	37.88	48.09	33.32
39.17	940	40.49	38.30	45.48	36.24	48.15	31.22
39.42	946	38.83	36.52	44.91	34.69	47.58	29.85
39.67	952	38.80	37.83	44.03	36.86	46.47	34.60
40.08	962	42.16	40.34	46.42	38.64	49.09	30.86
40.25	966	41.24	39.05	46.47	37.35	49.02	29.32
40.50	972	39.72	37.38	45.79	35.58	48.44	30.12
40.79	979	40.61	39.50	44.98	39.15	47.28	35.35
40.96	983	41.71	39.42	46.71	37.82	49.02	30.62
41.13	987	40.51	38.08	46.10	36.86	48.78	29.23
41.46	995	38.54	36.36	44.99	34.78	47.54	29.62
41.54	999	38.19	36.00	44.63	34.54	47.18	31.62
41.63	1,009	38.63	36.94	44.47	35.96	46.79	33.78
41.71	1,016	39.67	38.57	44.41	38.08	46.72	36.00
42.04	1,022	41.91	39.72	46.29	38.87	48.60	31.58
42.17	1,039	41.09	38.90	46.44	37.69	48.75	29.89
42.33	1,043	40.55	38.24	46.14	36.90	48.57	31.33
42.42	1,047	39.61	37.18	45.57	35.84	48.12	30.36
42.50	1,058	39.00	36.69	45.32	35.11	47.88	30.93

Table E.4 Temperature profiles for RUN IV (continued)

Time		Temperature					
days	hours	center	r+1	r+2	r-1	r-2	room
43.21	1,083	41.78	39.96	47.25	38.87	49.56	30.40
43.29	1,089	41.13	38.82	47.08	37.72	49.49	29.30
43.38	1,091	40.29	37.86	46.61	36.76	49.28	28.69
43.46	1,097	39.66	37.37	46.12	36.14	48.79	27.53
43.54	1,107	38.90	36.34	45.58	35.25	48.38	29.49
43.63	1,114	38.93	37.23	45.13	36.50	47.69	33.39
44.00	1,120	40.07	38.96	44.92	38.49	47.01	32.24
44.08	1,132	42.21	40.52	48.06	39.41	44.65	31.38
44.17	1,138	41.90	39.94	48.09	38.74	46.14	30.02
44.25	1,142	41.41	39.10	47.98	37.89	46.28	28.60
44.33	1,146	40.83	38.39	47.63	36.94	45.68	28.50
44.42	1,150	40.20	37.77	47.37	36.31	45.19	26.07
44.50	1,154	39.47	36.91	46.88	35.34	44.57	26.44
44.58	1,158	38.99	36.93	46.04	35.59	44.59	30.38
44.67	1,162	39.30	38.47	45.76	37.48	44.54	33.96
45.13	1,168	40.32	39.94	45.53	39.10	43.35	32.35
45.21		42.39	40.81	48.10	39.47	45.43	30.48
45.29		41.91	39.85	47.99	38.51	46.17	29.00
45.38		41.28	38.97	47.73	37.64	46.88	28.14
45.46		40.35	38.04	47.16	36.46	46.06	27.71
45.54		39.67	37.57	46.69	36.23	45.23	29.82
45.63		39.62	38.52	46.06	37.43	44.12	33.06
45.71		40.31	39.57	46.01	38.85	45.16	35.20
46.13		41.28	39.70	47.24	38.60	46.26	33.95
46.21		40.75	38.93	47.07	37.83	45.61	32.50
46.42		39.46	37.77	46.02	36.54	44.94	31.43
46.58		38.93	37.72	45.14	36.99	43.19	36.63
47.00		40.67	38.74	47.24	37.03	45.55	29.30
47.17		37.65	35.95	45.07	34.61	43.61	29.92
47.33		36.79	35.33	43.84	33.87	41.90	28.72
47.42		36.06	34.60	43.36	33.14	41.90	28.81
47.67		32.41	32.41	41.53	30.43	41.90	34.67
47.83		33.42	33.76	40.47	33.05	32.54	35.27
48.00		33.32	33.91	40.74	32.83	32.21	32.62

Appendix F

Thermal Conductivity Results

Table F.1 Temperatures in agar gel

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
0	-	23.68	230	5.44	27.70
5	1.61	23.70	235	5.46	27.78
10	2.30	23.70	245	5.48	27.85
15	2.71	23.70	250	5.50	27.91
20	3.00	23.70	255	5.52	27.98
25	3.22	23.69	260	5.54	28.04
30	3.40	23.69	265	5.56	28.10
35	3.56	23.68	270	5.58	28.16
40	3.69	23.67	275	5.60	28.22
45	3.81	23.66	280	5.62	28.28
50	3.91	23.66	285	5.63	28.33
55	4.01	23.70	290	5.65	28.39
60	4.09	23.79	295	5.67	28.45
65	4.17	23.93	300	5.69	28.50
70	4.25	24.08	305	5.70	28.55
75	4.32	24.24	310	5.72	28.61
80	4.38	24.41	315	5.74	28.67
85	4.44	24.58	320	5.75	28.71
90	4.50	24.74	325	5.77	28.77
95	4.55	24.90	330	5.78	28.82
100	4.61	25.05	335	5.80	28.87
105	4.65	25.19	340	5.81	28.92
110	4.70	25.33	345	5.83	28.96
115	4.74	25.47	350	5.84	29.01
120	4.79	25.61	355	5.86	29.06
125	4.83	25.73	360	5.87	29.10
130	4.87	25.85	365	5.89	29.15
135	4.91	25.96	370	5.90	29.20
140	4.94	26.08	375	5.91	29.24
145	4.98	26.19	380	5.93	29.28
150	5.01	26.30	385	5.94	29.33
155	5.04	26.40	390	5.95	29.37
160	5.08	26.51	395	5.97	29.41
165	5.11	26.61	400	5.98	29.45
170	5.14	26.72	405	5.99	29.49
180	5.19	26.91	415	6.02	29.57
190	5.25	27.09	425	6.04	29.66
195	5.27	27.16	430	6.05	29.69
200	5.30	27.25	435	6.06	29.73
205	5.32	27.32	440	6.08	29.77
210	5.35	27.39	445	6.09	29.81
215	5.37	27.47	450	6.10	29.84

Table F.1 Temperatures in agar gel (continued)

Time (sec)	ln t	Sample temperature (°C)	Time (sec)	ln t	Sample temperature (°C)
460	6.12	29.92	685	6.53	31.24
465	6.14	30.00	690	6.54	31.26
475	6.16	30.07	700	6.55	31.30
485	6.18	30.14	710	6.57	31.36
495	6.20	30.21	720	6.58	31.41
505	6.22	30.27	730	6.59	31.46
515	6.24	30.34	740	6.61	31.50
525	6.26	30.41	750	6.62	31.55
535	6.28	30.47	760	6.63	31.58
545	6.30	30.53	770	6.65	31.62
555	6.32	30.59	780	6.66	31.66
565	6.34	30.65	790	6.67	31.71
575	6.35	30.70	800	6.68	31.75
585	6.37	30.75	810	6.70	31.79
595	6.39	30.80	820	6.71	31.82
605	6.41	30.85	830	6.72	31.86
615	6.42	30.90	840	6.73	31.89
635	6.45	30.99	860	6.76	31.96
650	6.48	31.08	875	6.77	32.02
665	6.50	31.14	890	6.79	32.07
675	6.51	31.19	900	6.80	32.11
910	6.81	32.15	1,115	7.02	32.80
920	6.82	32.18	1,125	7.03	32.83
930	6.84	32.21	1,135	7.03	32.86
940	6.85	32.26	1,145	7.04	32.88
950	6.86	32.30	1,155	7.05	32.91
960	6.87	32.33	1,165	7.06	32.94
970	6.88	32.36	1,175	7.07	32.97
980	6.89	32.39	1,185	7.08	32.99
985	6.89	32.41	1,190	7.08	33.00
995	6.90	32.44	1,200	7.09	33.00
1,005	6.91	32.47	1,210	7.10	32.89
1,015	6.92	32.50			
1,025	6.93	32.53			
1,035	6.94	32.57			
1,045	6.95	32.61			
1,055	6.96	32.64			
1,065	6.97	32.66			
1,075	6.98	32.69			
1,085	6.99	32.72			
1,095	7.00	32.74			
1,100	7.00	32.75			
1,105	7.01	32.77			

Table F.2 Temperatures in sample 1

Time (sec)	ln t	Sample temperature (°C)	Time (sec)	ln t	Sample temperature (°C)
0	-	30.93	235	5.46	47.78
5	1.61	30.94	245	5.50	48.21
10	2.30	30.93	250	5.52	48.42
15	2.71	30.98	255	5.54	48.62
20	3.00	31.23	260	5.56	48.82
25	3.22	31.68	265	5.58	49.02
30	3.40	32.13	270	5.60	49.21
35	3.56	32.54	275	5.62	49.41
40	3.69	33.00	280	5.63	49.58
45	3.81	33.50	285	5.65	49.74
50	3.91	34.03	290	5.67	49.77
55	4.01	34.57	295	5.69	49.68
60	4.09	35.12			
65	4.17	35.68			
70	4.25	36.23			
75	4.32	36.76			
80	4.38	37.29			
85	4.44	37.81			
90	4.50	38.30			
95	4.55	38.79			
100	4.61	39.27			
105	4.65	39.72			
110	4.70	40.16			
115	4.74	40.61			
120	4.79	41.02			
125	4.83	41.44			
130	4.87	41.83			
135	4.91	42.21			
140	4.94	42.57			
145	4.98	42.92			
150	5.01	43.26			
160	5.08	43.91			
170	5.14	44.53			
175	5.16	44.81			
180	5.19	45.11			
185	5.22	45.38			
190	5.25	45.65			
195	5.27	45.91			
200	5.30	46.16			
210	5.35	46.65			
220	5.39	47.12			
225	5.42	47.34			

Table F.3 Temperatures in sample 2

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
0	-	33.25	235	5.46	39.94
5	1.61	33.48	245	5.50	40.09
10	2.30	33.75	250	5.52	40.16
15	2.71	34.01	255	5.54	40.23
20	3.00	34.27	260	5.56	40.30
25	3.22	34.52	265	5.58	40.36
30	3.40	34.75	270	5.60	40.43
35	3.56	34.98	275	5.62	40.49
40	3.69	35.19	280	5.63	40.56
45	3.81	35.39	285	5.65	40.62
50	3.91	35.59	290	5.67	40.69
55	4.01	35.78	295	5.69	40.75
60	4.09	35.96	300	5.70	40.80
65	4.17	36.14	305	5.72	40.87
70	4.25	36.30	310	5.74	40.92
75	4.32	36.47	315	5.75	40.99
80	4.38	36.62	320	5.77	41.04
85	4.44	36.78	325	5.78	41.10
90	4.50	36.92	330	5.80	41.17
95	4.55	37.07	335	5.81	41.22
100	4.61	37.21	340	5.83	41.27
105	4.65	37.33	345	5.84	41.33
110	4.70	37.48	350	5.86	41.38
115	4.74	37.61	355	5.87	41.44
120	4.79	37.73	360	5.89	41.49
125	4.83	37.84	365	5.90	41.54
130	4.87	37.97	370	5.91	41.59
135	4.91	38.07	375	5.93	41.64
140	4.94	38.19	380	5.94	41.69
145	4.98	38.31	385	5.95	41.73
150	5.01	38.42	390	5.97	41.78
160	5.08	38.62	400	5.99	41.87
170	5.14	38.83	410	6.02	41.96
180	5.19	39.02	420	6.04	42.05
185	5.22	39.10	425	6.05	42.09
190	5.25	39.20	430	6.06	42.14
200	5.30	39.38	440	6.09	42.23
205	5.32	39.47	445	6.10	42.26
210	5.35	39.56	450	6.11	42.31
215	5.37	39.64	455	6.12	42.36
220	5.39	39.71	460	6.13	42.40
225	5.42	39.79	465	6.14	42.44

Table F.3 Temperatures in sample 2 (continued)

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
475	6.16	42.52	735	6.60	44.36
480	6.17	42.57	745	6.61	44.43
485	6.18	42.60	750	6.62	44.45
490	6.19	42.64	755	6.63	44.48
495	6.20	42.68	760	6.63	44.51
520	6.25	42.90	765	6.64	44.54
525	6.26	42.95	770	6.65	44.57
530	6.27	42.99	775	6.65	44.58
535	6.28	43.02	780	6.66	44.61
540	6.29	43.06	785	6.67	44.64
545	6.30	43.11	790	6.67	44.66
550	6.31	43.14	795	6.68	44.69
555	6.32	43.18	800	6.68	44.72
560	6.33	43.23	805	6.69	44.74
565	6.34	43.27	810	6.70	44.76
570	6.35	43.32	815	6.70	44.79
575	6.35	43.35	820	6.71	44.80
580	6.36	43.38	825	6.72	44.83
585	6.37	43.41	830	6.72	44.86
590	6.38	43.46	835	6.73	44.88
595	6.39	43.49	840	6.73	44.91
600	6.40	43.52	845	6.74	44.93
605	6.41	43.55	850	6.75	44.96
610	6.41	43.58	855	6.75	44.98
615	6.42	43.61	860	6.76	45.00
620	6.43	43.64	865	6.76	45.03
625	6.44	43.67	870	6.77	45.05
630	6.45	43.71	875	6.77	45.07
640	6.46	43.78	885	6.79	45.16
650	6.48	43.84	895	6.80	45.22
660	6.49	43.92	905	6.81	45.27
665	6.50	43.95	910	6.81	45.29
670	6.51	43.97	915	6.82	45.32
675	6.51	44.01	920	6.82	45.35
680	6.52	44.04	925	6.83	45.38
690	6.54	44.11			
695	6.54	44.14			
700	6.55	44.16			
705	6.56	44.19			
710	6.57	44.22			
715	6.57	44.24			
720	6.58	44.27			

Table F.4 Temperatures in sample 3

Time (sec)	ln t	Sample temperature (°C)	Time (sec)	ln t	Sample temperature (°C)
0	-	30.94	235	5.46	40.07
5	1.61	30.94	240	5.48	40.10
10	2.30	30.94	245	5.50	40.17
15	2.71	30.97	250	5.52	40.25
20	3.00	31.23	255	5.54	40.32
25	3.22	31.67	260	5.56	40.39
30	3.40	32.19	265	5.58	40.46
35	3.56	32.71	270	5.60	40.59
40	3.69	33.20	275	5.62	40.73
45	3.81	33.65	280	5.63	40.84
50	3.91	34.07	285	5.65	40.86
60	4.09	34.80	295	5.69	41.02
65	4.17	35.13	300	5.70	41.11
70	4.25	35.43	305	5.72	41.17
75	4.32	35.70	310	5.74	41.23
80	4.38	35.96	315	5.75	41.27
90	4.50	36.41	325	5.78	41.32
95	4.55	36.62	330	5.80	41.34
100	4.61	36.82	335	5.81	41.37
105	4.65	37.00	340	5.83	41.42
110	4.70	37.19	345	5.84	41.47
120	4.79	37.54	355	5.87	41.55
125	4.83	37.70	360	5.89	41.57
130	4.87	37.84	365	5.90	41.60
135	4.91	37.98	370	5.91	41.67
140	4.94	38.10	375	5.93	41.72
145	4.98	38.22	380	5.94	41.75
150	5.01	38.34	385	5.95	41.77
155	5.04	38.46	390	5.97	41.81
160	5.08	38.66	395	5.98	41.86
165	5.11	38.93	400	5.99	41.91
170	5.14	39.11	405	6.00	41.96
175	5.16	39.24	410	6.02	42.03
180	5.19	39.35	415	6.03	42.08
185	5.22	39.46	420	6.04	42.11
190	5.25	39.55	425	6.05	42.16
195	5.27	39.62	430	6.06	42.19
200	5.30	39.71	435	6.08	42.23
205	5.32	39.81	440	6.09	42.27
210	5.35	39.88	445	6.10	42.30
220	5.39	40.03	455	6.12	42.39

Table F.4 Temperatures in sample 3 (continued)

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
470	6.15	42.52	710	6.57	43.85
475	6.16	42.57	715	6.57	43.89
480	6.17	42.60	720	6.58	43.92
485	6.18	42.63	725	6.59	43.95
490	6.19	42.66	730	6.59	43.98
495	6.20	42.69	735	6.60	44.02
500	6.21	42.72	740	6.61	44.04
505	6.22	42.74	745	6.61	44.05
510	6.23	42.78	750	6.62	44.07
515	6.24	42.80	755	6.63	44.10
520	6.25	42.83	760	6.63	44.13
525	6.26	42.85	765	6.64	44.16
530	6.27	42.88	770	6.65	44.20
535	6.28	42.91	775	6.65	44.23
540	6.29	42.96	780	6.66	44.26
545	6.30	43.00	785	6.67	44.30
550	6.31	43.05	790	6.67	44.32
555	6.32	43.10	795	6.68	44.34
560	6.33	43.14	800	6.68	44.36
565	6.34	43.16	805	6.69	44.40
570	6.35	43.20	810	6.70	44.42
575	6.35	43.21	815	6.70	44.46
580	6.36	43.23	820	6.71	44.48
585	6.37	43.27	825	6.72	44.51
590	6.38	43.30	830	6.72	44.53
595	6.39	43.31	835	6.73	44.56
600	6.40	43.34	840	6.73	44.58
605	6.41	43.38	845	6.74	44.59
610	6.41	43.41	850	6.75	44.61
620	6.43	43.45	860	6.76	44.64
625	6.44	43.44	865	6.76	44.66
630	6.45	43.48	870	6.77	44.68
640	6.46	43.56	880	6.78	44.71
645	6.47	43.58	885	6.79	44.74
650	6.48	43.58	890	6.79	44.79
655	6.48	43.61	895	6.80	44.82
660	6.49	43.64	900	6.80	44.87
670	6.51	43.70	910	6.81	44.94
675	6.51	43.71	915	6.82	44.97
680	6.52	43.73	920	6.82	44.98
690	6.54	43.76	930	6.84	44.99
695	6.54	43.78	935	6.84	45.01

Table F.5 Temperatures in sample 4

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
0	-	30.14	235	5.46	37.11
5	1.61	30.14	240	5.48	37.19
10	2.30	30.13	245	5.50	37.27
15	2.71	30.13	250	5.52	37.34
20	3.00	30.17	255	5.54	37.42
25	3.22	30.34	260	5.56	37.50
30	3.40	30.60	265	5.58	37.56
35	3.56	30.90	270	5.60	37.64
40	3.69	31.20	275	5.62	37.70
45	3.81	31.50	280	5.63	37.76
50	3.91	31.79	285	5.65	37.82
55	4.01	32.07	290	5.67	37.88
60	4.09	32.34	295	5.69	37.94
70	4.25	32.84	305	5.72	38.06
75	4.32	33.06	310	5.74	38.12
80	4.38	33.28	315	5.75	38.18
85	4.44	33.47	320	5.77	38.22
90	4.50	33.67	325	5.78	38.27
95	4.55	33.86	330	5.80	38.33
100	4.61	34.03	335	5.81	38.37
105	4.65	34.20	340	5.83	38.43
115	4.74	34.51	350	5.86	38.54
120	4.79	34.67	355	5.87	38.58
125	4.83	34.81	360	5.89	38.63
130	4.87	34.94	365	5.90	38.66
135	4.91	35.08	370	5.91	38.70
140	4.94	35.20	375	5.93	38.71
145	4.98	35.33	380	5.94	38.77
160	5.08	35.70	395	5.98	38.98
170	5.14	35.92	405	6.00	39.09
175	5.16	36.03	410	6.02	39.16
180	5.19	36.14	415	6.03	39.21
185	5.22	36.25	420	6.04	39.24
190	5.25	36.35	425	6.05	39.29
195	5.27	36.45	430	6.06	39.33
200	5.30	36.54	435	6.08	39.38
205	5.32	36.62	440	6.09	39.42
210	5.35	36.71	445	6.10	39.47
215	5.37	36.79	450	6.11	39.52
220	5.39	36.87	455	6.12	39.59
225	5.42	36.96	460	6.13	39.64

Table F.5 Temperatures in sample 4 (continued)

Time (sec)	ln t	Sample temperature (^{o}C)	Time (sec)	ln t	Sample temperature (^{o}C)
470	6.15	39.72	710	6.57	41.51
475	6.16	39.74	715	6.57	41.54
480	6.17	39.79	720	6.58	41.57
490	6.19	39.87	730	6.59	41.62
495	6.20	39.91	735	6.60	41.65
500	6.21	39.95	740	6.61	41.68
510	6.23	40.04	750	6.62	41.74
520	6.25	40.12	760	6.63	41.80
530	6.27	40.22	770	6.65	41.87
545	6.30	40.35	785	6.67	41.96
555	6.32	40.40	795	6.68	42.02
565	6.34	40.50	805	6.69	42.07
575	6.35	40.58	815	6.70	42.14
585	6.37	40.66	825	6.72	42.20
595	6.39	40.75	835	6.73	42.25
605	6.41	40.80	845	6.74	42.31
615	6.42	40.85	855	6.75	42.37
625	6.44	40.91	865	6.76	42.42
630	6.45	40.95	870	6.77	42.44
645	6.47	41.06	885	6.79	42.50
660	6.49	41.15	900	6.80	42.55
685	6.53	41.33	925	6.83	42.64
695	6.54	41.40	935	6.84	42.68
950	6.86	42.73	1,195	7.09	43.70
960	6.87	42.77	1,205	7.09	43.73
980	6.89	42.85	1,225	7.11	43.82
990	6.90	42.90	1,235	7.12	43.86
1,005	6.91	42.98	1,245	7.13	43.89
1,015	6.92	43.03	1,255	7.13	43.92
1,025	6.93	43.08	1,265	7.14	43.95
1,040	6.95	43.14	1,280	7.15	44.00
1,050	6.96	43.20	1,290	7.16	44.02
1,060	6.97	43.25	1,300	7.17	44.04
1,070	6.98	43.27	1,310	7.18	44.06
1,080	6.98	43.31	1,320	7.19	44.09
1,090	6.99	43.32	1,330	7.19	44.11
1,100	7.00	43.35	1,340	7.20	44.14
1,110	7.01	43.38	1,350	7.21	44.17
1,120	7.02	43.41	1,360	7.22	44.19
1,130	7.03	43.45	1,370	7.22	44.23
1,150	7.05	43.53	1,390	7.24	44.26
1,165	7.06	43.57	1,405	7.25	44.28
1,175	7.07	43.60	1,415	7.25	44.30

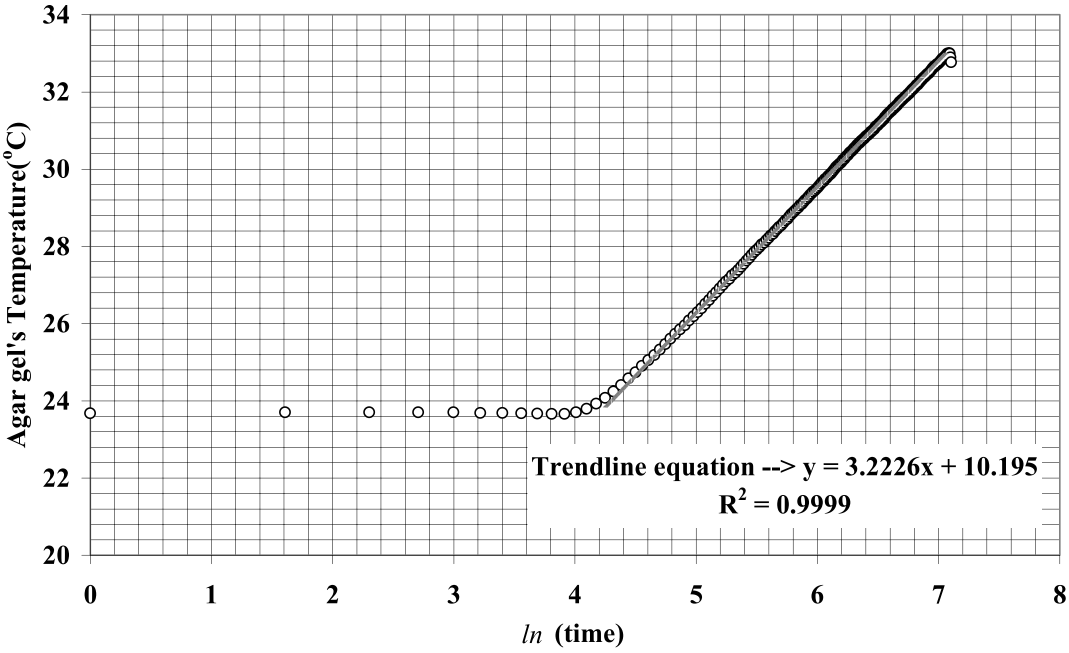


Figure F.1 Agar gel calibration curve

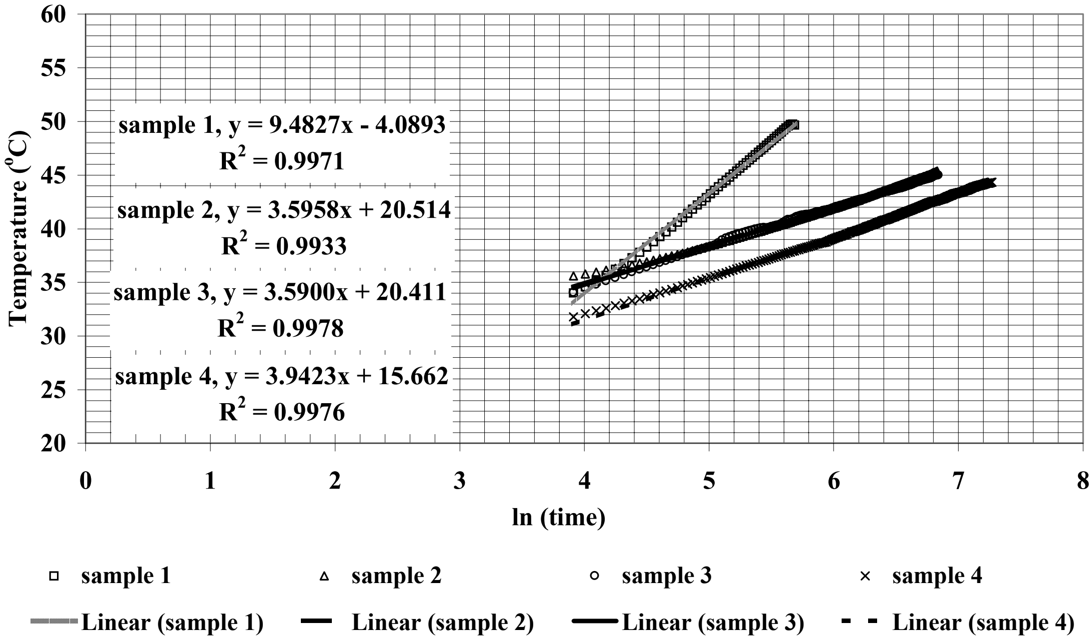


Figure F.2 Linear slope of composting samples

Appendix G

Computer Program

Computer program

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10      REM:  TRANSIENT  HEAT  CONDUCTION  IN  A  CYLINDER  WITH  INTERNAL
        HEAT GENERATION  BY  EXPLICIT  METHOD
20      REM: CONVECTION  BOUNDARY  CONDITIONS  ARE  ASSUMED
30      REM: UNIFORM  INITIAL  TEMPERATURE  WITH  CONSTANT  CONVECTION
        BOUNDARY  CONDNS
40      DIM  T ( 1000 ) , TT( 1000 ) , R( 50 ) ,TEXP( 1000 ) , TEST( 1000 )
50      RADIUS  = .5  : REM: CYLINDER  RADIUS  ( m )
60      H=5  : REM:  SURFACE  HEAT  TRANSFER  COEFFICIENT  ( W/M^2  deg  C )
70      TAIR=30!   : REM:  SURROUNDING  FLUID  TEMPERATURE  ( deg c )
80      COND=.55 : REM:  THERMAL  CONDUCTIVITY  OF  SLAB  ( W/m^2.degC )
90      ALPHA=1.7/1E+07:  REM:  THERMAL  DIFFUSIVITY  ( m^2/s )
100     TIN=27.38 :REM:  UNIFORM  INITIAL  TEMPERATURE  DISTRIBUTION
110     INPUT  “Internal  heat  generation  ( W/m^3 )  =”;HEAT
120     INPUT  “Number  of  space  increments  ( any  even  or  odd  number )”;N
125     LPRINT  “Internal  Heat  Generation  ( W/m^3 ):”;HEAT
130     FGRID=.25   :   REM:   FGRID  is  assumed  to  be  0.25  for  stability.
140     DELX=RADIUS/N
150     DELT = ( DELX*DELX*FGRID ) /ALPHA
160     N1=N+1   :  REM:   NO.  OF  NODAL  POINTS
170     FOR  I = 1  TO  N1  :   REM:   INITIALIZE  R( I )  AND  T( I )  VALUES
180     R( I ) = DELX*( I-1 )   :REM:  RADIAL  DISTANCE  OF  NODE  I  FROM  CENTER
190     T( I ) = TIN
200     NEXT  I
210     LPRINT:LPRINT  “Time ( h )    Temp ( est )     Temp ( exp )    Error”
220     SUM=0
230     J = 1  :  REM:  FIRST  TIME  INCREMENT
240     FOR  I = 1  TO  N1  STEP  N
250     IF  I>1  GOTO 270
260     TT( I ) = 4*FGRID*T( I+1 )+( 1-4*FGRID )*T( I )+( FGRID*DELX*DELX*HEAT )
        /COND : GOTO 280
270     TT ( N1 ) = ( T( N )+H*DELX*TAIR/COND + ( DELX*DELX*HEAT*.5/COND ) ) /
        (1+H*DELX/COND)
280     NEXT  I
290     FOR  I = 2  TO  N
300     TT( I ) = ( FGRID/2 ) * ( (2+DELX/R( I ) ) *T( I+1 )+( 2-DELX/R( I ) )*T( I-1 )+( 2/FGRID-
        4 )*T( I )+(2*DELX*DELX*HEAT/COND ) )
310     NEXT I
320     TIME = J*DELT/ (3600)    ‘Time in hours.
330     TEXP ( J ) = -.0012*TIME*TIME+.3075*TIME+28.99
340     TEST ( J ) =T( 1 )
350     SUM=SUM+(TEXP( J ) –TEST( J ) ) ^2
360     DIFF  =  SUM^ .5
370     LPRINT  TIME ,T( 1 ) ,TEMP( J ) ,DIFF
380     FOR  I=1   TO  N1
390     T( I ) =TT( I )
400     NEXT  I
410     J=J+1
420     IF  J>60  GOTO  440  :  REM:  NUMBER  OF  TIME  STEPS  (DELT)
430     GOTO  240
440     END
```

Biography

Putong Ratanamalaya was born on March 2nd, 1974, in Nakhon Ratchasima, North Eastern of Thailand. After grade 10 and 10 at Trium Udom Suksa, Bangkok, Thailand, she went to USA to finish 12th grade at Madison Consolidated High School, Madison, Indiana. In 1992, the author started studying in a Pre-Engineering Program at Marshall University, West Virginaia. Afterwards, she studied and received a Bachelor Degree of Science in Environmental Engineering Technology from Pennsylvania State University, Pennsylvania. Subsequently, she had come back to Thailand in 1998 and started studying in a masters program in Environmental Engineering at Suranaree University of Technology, in 1999.