CONTROLLED TEMPERATURE FORCED AIR COMPOSTING

Thesis for the Degree of M. Sc.
MICHIGAN STATE UNIVERSITY

Chang Moon Bek

1956

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By

Chang Moon Bek

An Abstract

Submitted to the College of Graduate Studies of Michigan

State University of Agriculture and Applied Science

in Partial fulfillment of the requirements

for the degree of

Master of Science

Department of Civil and Sanitary Engineering

December 1956

Approved____________________________________

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A study was made of the effects of controlled temperature and forced air on composting solid organic matter.

A laboratory batch-type digester of 4 gallons working capacity was used without any stirring mechanisms. Solid organic matter used for this study consisted of freshly ground food which was carefully proportioned to represent a typical garbage.

Temperature of the composting matter was controlled at 40, 45, 50, 55, and 60^{o}C levels by copper coils. Amount of cooling water flow in the coils was regulated by a solenoid valve connected in such a way as to permit the flow of cooling water when the temperature of the composting matter exceeded the set level on a thermostat.

Constant flow of heated air was supplied through a porous plastic false bottom to the composting matter. The temperature of the air supplied to the unit was set at the same level as that of the composting matter.

Physical and chemical analyses for evaluating the degree of decomposition during the composting were outlined and results have been reported.

All experiments required about 9 days for stabilization of solid organic matter.

Air flow ranged from 20 to 29 cubic feet per day per

pound of dry weight of material. A porous plastic false bottom was found to be a satisfactory method of providing an uniform distribution of air into the unit. The success of this technique indicates that turning and stirring may not be necessary in successful composting operations.

The volatile solids reduction varied with temperature, and maximum reduction in volatile solids was noted at 40°C level. The order of volatile solids reduction was: 40, 50, 55, 45, and 60°C. Moisture content showed a decrease in the experiments where high temperature levels were maintained. Porosity showed a decrease from 80.6 to 75.6 per cent.

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Acknowledgment

The author wishes to express his sincere thanks to Dr. R. F. McCauley, Professor F. R. Theroux, and Dr. K. L. Schulze, for their helpful guidance and assistance in connection with this work.

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INTRODUCTION

Composting is primarily an aerobic process in which aerobic microorganisms utilize large quantities of oxygen in decomposing organic matter to a relatively stable humus.

In aerobic composting numerous physical factors directly influence the rate at which the organic matter is decomposed to a humus. In order to obtain maximum efficiency in the composting process, it is necessary to control these influencing factors whenever feasible. In large field operations, such factors are not easily controlled; moreover, proper control is now impractical because of insufficient fundamental understandings of composting process. However, in laboratory studies, the method of control can be studied scientifically. Such control methods can perhaps later be applied to larger scale operations.

It was intended in this work to study the effects of two important variables, controlled temperature and forced air supply, on the composting process.

SECTION II

LITERATURE REVIEW

The field of composting has been under investigation rather extensively during the past several years by Scott(1), Van Vuren(2), by Gotaas and his associates--McGauhey, Goluke, and Cord(3,4,5,7), by Michigan State University(6,8,9), and by several others in different parts of the world. Both field and laboratory investigations have been reported.

The basic biological principle is the same for field and laboratory aerobic composting, the major difference between the operations being the degree of controls. McCauley(24) has stated that oxygen penetrates into voids of the material where it dissolves in the liquid films, and is carried to aerobic microorganisms, which are active agents in decomposing organic matter. It was Gotaas's opinion that a completely aerobic condition could not be maintained during the composting process even under well controlled conditions because of the effect of particle sizes(10). Probably, the process is a combination of aerobic and anaerobic decomposition with aerobic organisms being more dominant(24).

Batzer(26) has stated that ground organic matter such as garbage had fineness modulus ranging from 0.4 to 0.9. Anaerobic conditions probably existed in the center portion of particles of this size because only minute amounts of oxygen could penetrate to such a depth in the material. However, on the outer portion of the individual particle the condition was aerobic since an ample supply of oxygen was available for the aerobic microorganisms.

Gotaas has stated that under suitable environmental conditions aerobic microorganisms were more active, and therefore the breakdown of organic matter was faster(10). For this reason, an efficient composting process must be well controlled. The important variables which Gotaas has mentioned included: 1) Particle size; 2) Seeding or Blending; 3) Placement of raw material; 4) Moisture Content; 5) Oxygen Supply; 6) Temperature; 7) Hydrogen-ion Concentration. Other factors related to composting also included: 1) Time Required for Composting; 2) Testing and Judging the Conditions of Compost during the decomposition; 3) Weight-Volume Relationship; 4) Free Air Space; 5) Fineness Modulus(9,17,26).

A. PRINCIPLE VARIABLES IN COMPOSTING

1. Particle Sizes

Gotaas and co-workers at the University of California(12) have stated that particle sizes were very important to the composting process. This was because the digestion of the garbage and other organic waste material was accomplished by microorganisms which could utilize small particles more rapidly than larger ones.

According to Gotaas(10), good grinding gave the following beneficial features: 1) more oxygen was available to the microorganisms because of the greater surface area; 2) material was rendered more susceptible to bacterial invasion by exposing a larger surface to attack and destroying the natural resistance of vegetation to microbial invasion. Goluke(18) stated that grinding provided initial aeration, produced homogeneous materials, and provided a structure that made the material more responsive to moisture control and aeration.

Opinions regarding grinding differ. Gotaas(10) has stated that the most desirable particle size for composting of refuse was less than 2 inches in the largest dimension. Wiley(11) also working with refuse, reported that two grindings, first at 1 $\frac{7}{8}$ inches, and then at $\frac{5}{8}$ inch had produced satisfactory results. Michigan State University(8), working with windrow compost, reported that very fine grinding to modulus of fineness of 0.4 to 0.9 with a Ray Mo Grinder also produced good results. However, further shredding was necessary in windrows to prevent anaerobic conditions due to half-inch balls formed in the piles. According to the University of California(12), a particle size of 1 inch was most efficient in composting of municipal garbage.

Batzer(26) stated that excessively fine grinding was to be avoided because fine particles packed together forming large particles, and also because fine particles will be dissolved.

2. Seeding or Blending

Seeding or blending of raw organic solids with partially composted material may not be essential to satisfactory composting, but seemed to have marked advantages. According to Anderson(19), solid organic wastes from a municipality usually had moisture contents of 65 to 75 per cent. Seeding of raw garbage with relatively dry and partially digested compost, has been found by Gotaas(10) to reduce the moisture content to any desired level. Shell(17) found that seeding helped to prevent excessive compaction due to the pasty characteristic of wet raw organic waste. McCauley(24) has mentioned that seeding provided a large population of organisms, which were capable of immediately beginning the digestion of raw organic solids. Snell(27) recommended 2 to 10 per cent seeding with very active and partially composted material.

3. Placement of Material

Gotaas(10) has stated that the method of placement of ground raw organic solids into a digester should depend upon the type of digester in use. Continuous flow type digesters present no problem because the material is continuously stirred by a mixing mechanism; however, in batch-type digesters the degree of compaction has a marked effect(9,10).

Excessive compaction will prevent equal flow of air throughout the material due to a channeling effect(9). The method of placing the organic matter into batch-type digesters required further investigation and no completely satisfactory process seems to have yet been developed.

4. Moisture Content

Moisture also has a marked effect on aerobic composting. Water is an essential constituent of cell protoplasm and seems to dissolve nutrients rending them available for aerobic microorganisms(12).

In practical aerobic composting, a high moisture content should be avoided because water displaces air from the interconnected space between the particle, and gives rise to anaerobic conditions. On the other hand, excessively low moisture should be avoided because insufficient moisture deprives the microorganisms of water needed for their metabolism, and consequently retards the activity(10).

According to Gotaas(10), moisture content was found particularly critical in digester operations. Moisture levels above 60 per cent often resulted in anaerobic conditions, during Michigan State University studies(8).

Opinions regarding optimum moisture content for good composting has varied a great deal from one investigator to another. University of California(12) stated that a moisture content of 40 to 60 per cent was most satisfactory for composting of refuse in windrows. Scott(1) found 50 to 60 per cent was optimum for manure composting. Acharya(13) believed that 45 to 50 per cent was good for manure and sludge composting. Wiley(11) found that for refuse and garbage composting a range between 55 to 60 per cent was satisfactory. Waksman(14) stated that moisture content of 75 to 80 per cent was optimum for manure composting. According to Snell(27), optimum moisture range lay between 53 to 58 per cent for garbage. Quartly(31) found 40 to 66 per cent to be most satisfactory for municipal garbage composting.

Aerobic decomposition can proceed at any moisture content between 30 to 100 per cent, provided the supply of air can provide oxygen to the microorganisms(10). Michigan State University(8,9) showed that decomposition took place at any moisture content, but that, with garbage, efficient aerobic composting required the moisture content to be below 60 per cent and above 50 per cent. Unquestionably, optimum moisture content depends upon the type of material being composted, with higher moisture contents for refuse than for domestic garbage(24).

5. Oxygen Supply

Oxygen is supplied to aerobic organisms by mass movement and diffusion of air and by forced aeration. Shell(17) found that oxygen supply by mass movement and by diffusion was not adequate to maintain aerobic condition in windrows. McCauley(24) stated that oxygen must be supplied by forced aeration if near-aerobic conditions were to be maintained in a batch-type digester.

Gotaas(10) found that excessively high aeration rates caused rapid cooling and dehydration, and that very low aeration rates developed anaerobic conditions. Studies have been conducted by different workers to establish optimum aeration rates. Shell(17) stated that diffusion and mass movement would supply only 5 per cent of the total oxygen requirement of an active composting mass. Maximum oxygen demand at 58 per cent moisture was found by Shell(17) to be 0.55 cu ft oxygen /day/lb dry solids. Michigan State University studies(9) indicated that in a barrel-type digester an aeration rate of 2 to 4 cu ft of air/day/lb dry solids was satisfactory.

Rate of air supply has a marked effect on temperature. When air was supplied by Wiley(11) at 4 to 6.4 cu ft/day/lb volatile solids the maximum temperature was reached on the seventh day. An air supply of 9 to 29 cu ft /day/lb resulted in a maximum temperature on the fourth day(11). Wiley also observed that heated air had no effect on the rate of composting process.

Michigan State University studies(9) with a barrel-type digester showed that when a controlled flow of air passed through the material, the temperature remained near 60°C; however, when the air flow was discontinued a sharp drop in the temperature was observed, indicating a reduction in the metabolism rate. When the air flow was resumed, temperature was observed to rise to the range which had been previously observed.

Various tests in connection with batch-type composting have shown that oxygen levels dropped rapidly at depths of composting material greater than 2 inches. It was also observed that the oxygen levels decreased but did not drop to zero at 4 to 10 inch depths(9). These studies indicated that the diffusion rate decreased when depth of the material was increased.

Shell(17) estimated that oxygen supplied to the composting material by diffusion alone was not more than 5 per cent of the maximum oxygen requirements at moisture contents of 58 to 60 per cent. Michigan State University experiments(9) indicated that maximum oxygen utilization was 420×10^{-4} moles /hr/100 grams dry solids at 45°C and at 56 ± 2 per cent moisture. This is approximately 0.166 cu ft of air/hr/100 grams of dry weight of material as shown in Figures 1,2, and 3. Studies on maximum oxygen uptake and demand during periods of rapid digestion seem to have indicated that the oxygen demand could be met to only a very limited degree by diffusion. The wide difference between the measured rate of oxygen uptake and oxygen diffusion indicated that diffusion alone could not supply oxygen at a high enough rate to maintain a completely aerobic bacterial population at a depth greater than 2 to 3 inches.

Under many circumstances, and perhaps under most circumstances,forced air may be necessary to supply adequate

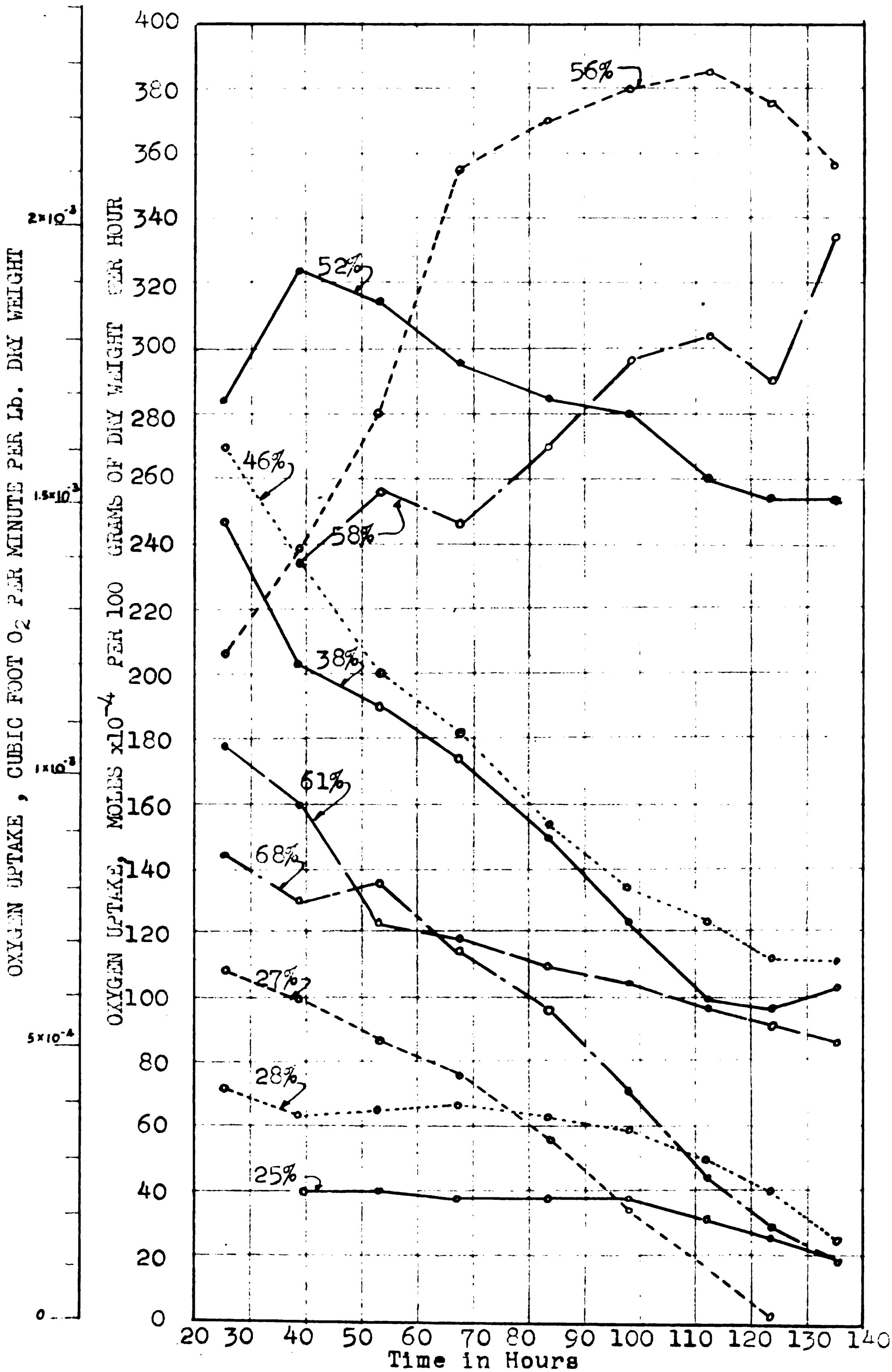


FIGURE-1 : OXYGEN UPTAKE AT VARIOUS MOISTURE CONTENTS
(Moving average area for Oxygen uptake)

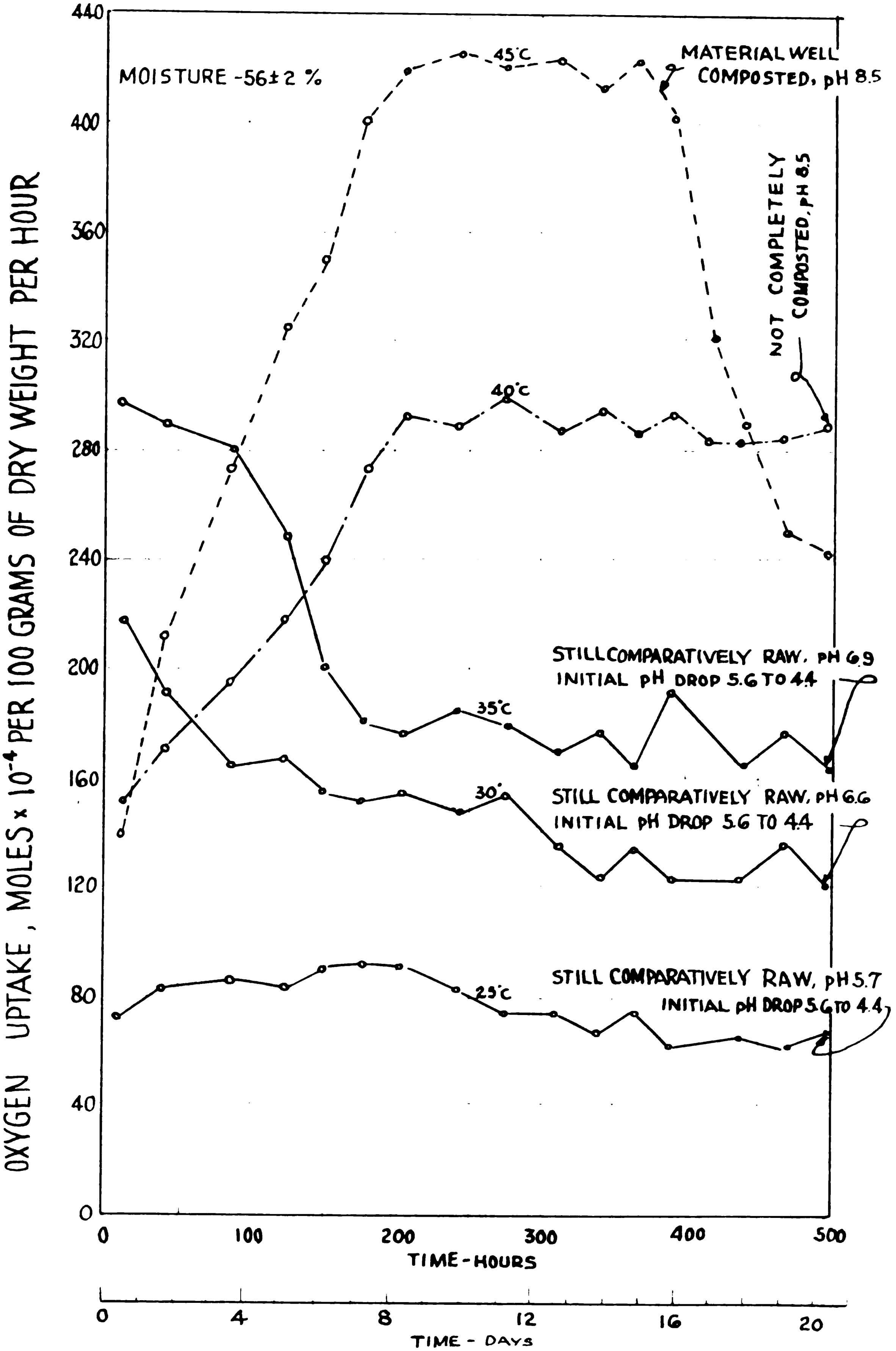


FIGURE-2: OXYGEN UPTAKE AT VARIOUS TEMPERATURES

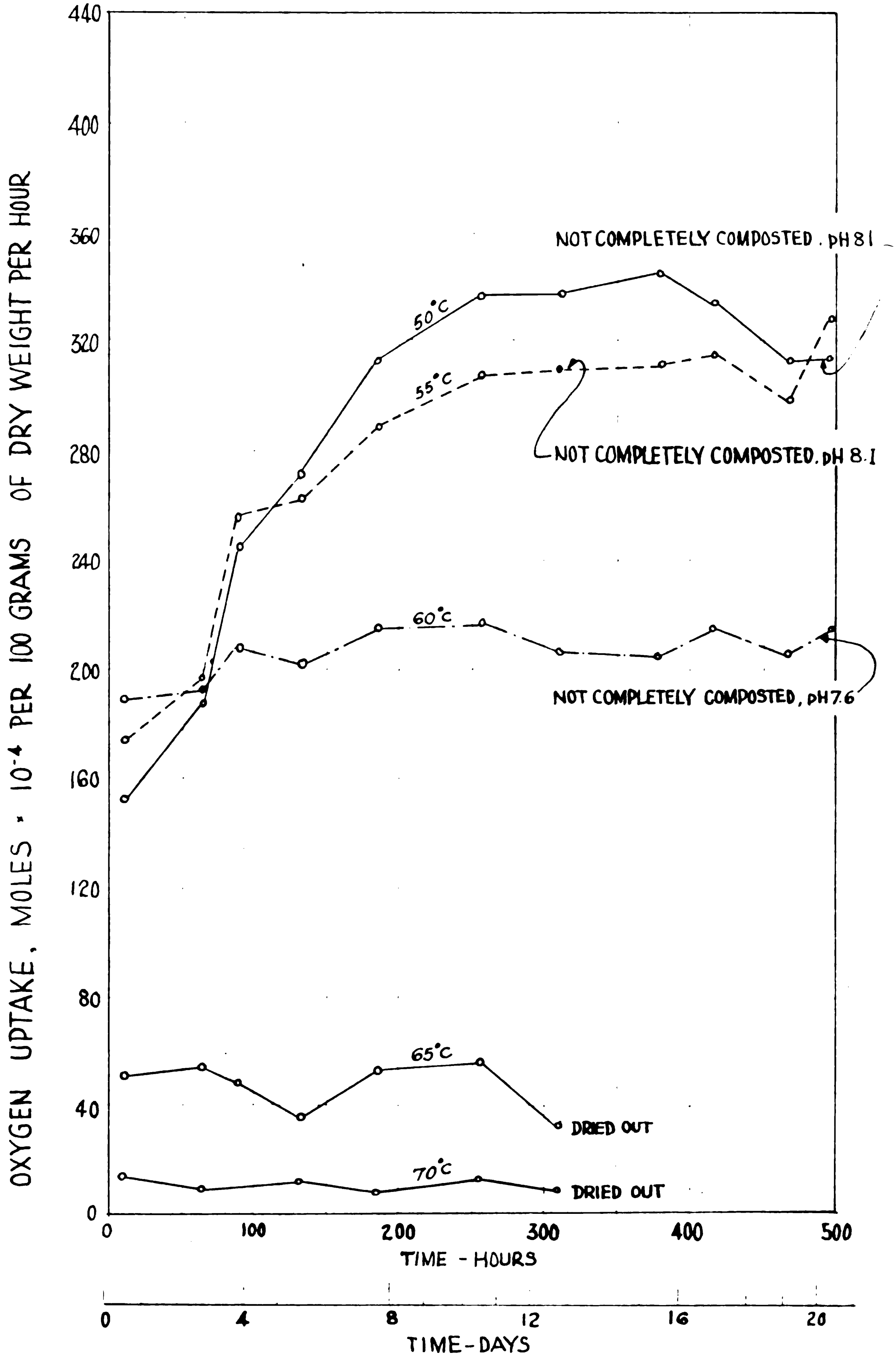


FIGURE-3: OXYGEN UPTAKE AT VARIOUS TEMPERATURES

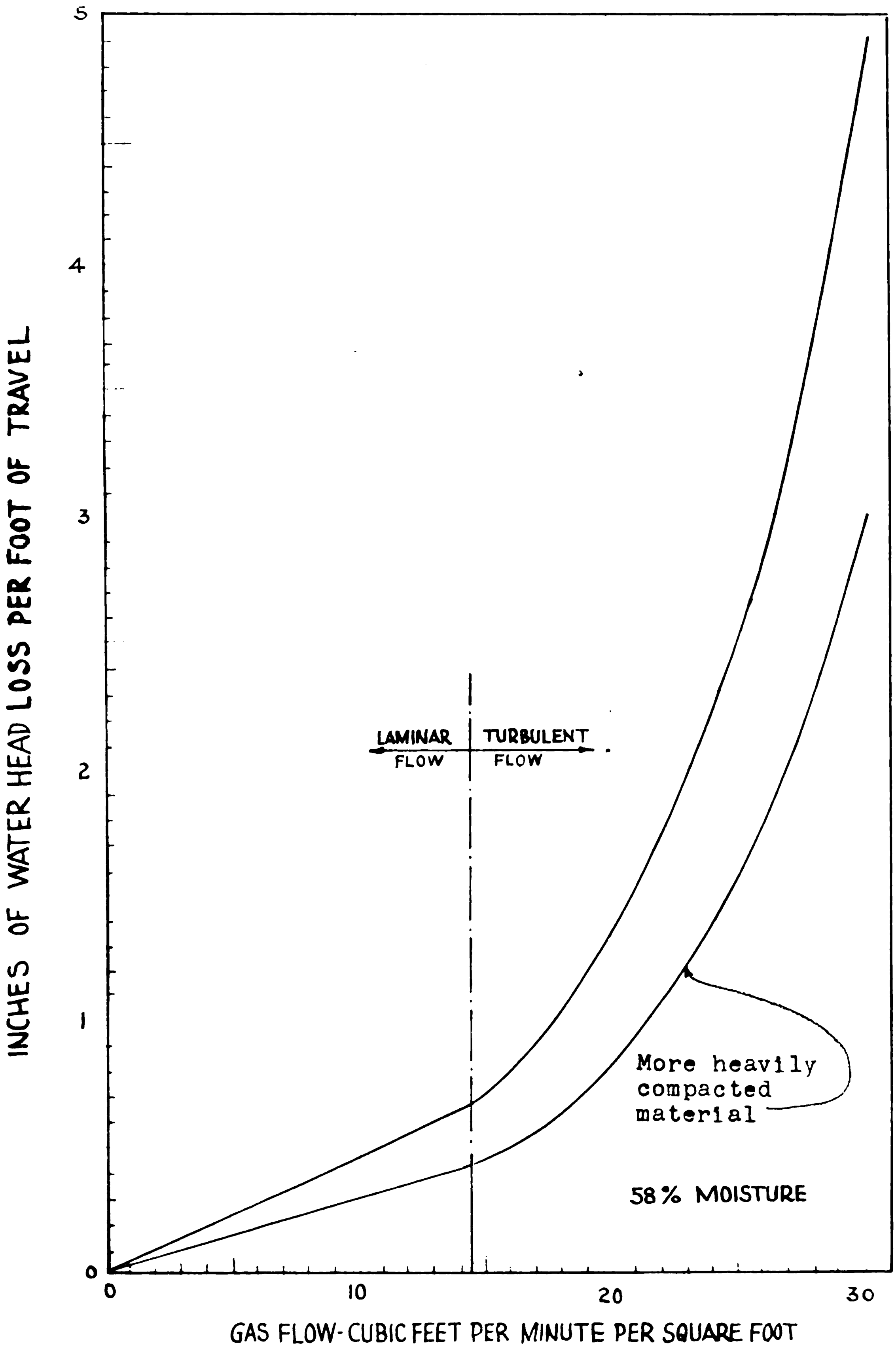


FIGURE - 4 : RESISTANCE TO MASS MOVEMENT OF AIR THROUGH PORE SPACES OF GROUND GARBAGE oxygen to maintain successful composting(24).

Ludwig(30) observed that maximum oxygen utilization at 45°C was 9.55 mg Oxygen /hr/100 grams, or 0.112 cu ft of air/hr/100 grams dry solids. Comparing the Ludwig and Michigan State University results on maximum oxygen uptake, it can be said that the maximum air requirement level was around 0.167 cu ft air/hr/100 grams of dry weight of organic material.

Wiley(11) used areation rates ranging between 10 to 30 cu ft/day/lb of volatile solids. Assuming that 20 cu ft/day/lb was the median value, the aeration rate was computed to be 0.183 cu ft/hr/100 grams volatile solids.

Upon the basis of these studies an aeration rate of 0.1 to 0.2 cu ft of air/hr/100 grams of dry weight of organic wastes at the moisture contents of 50 to 60 per cent seems to be indicated.

The tests by Snell(27) have shown that when air was passed at a rate of 0.25 cu ft/hr/sq ft, the flow was laminar. Above 0.25 cu ft/hr/sq ft, turbulent flows were observed as shown in Figure 4.

6. Temperatures

In aerobic composting, living organisms feed upon the organic matter and develop cell protoplasm from the nitrogen, phosphorous, carbon, and other nutrients. Much of the carbon serves as a source of energy for the organisms and is burned up and respired as carbon dioxide. Heat is released during the composting process. High temperatures are developed during the exothermic biological reaction, and are retained in the composting material because of good insulating properties which the material possesses(10).

According to Gotaas(10), decomposition of organic matter proceeded at a rapid rate in the thermophilic temperature range. When the temperature exceeded 45°C thermophilic organisms which thrived in the temperature ranges of 45 to 65°C developed and replaced the mesophilic organisms. Therefore, the active organisms in the aerobic composting process were the thermophilic aerobic bacteria, and decomposition took place more vigorously. Shorter time was required for stabilization at the thermophilic temperature than at the mesophilic temperature range.

Gotaas(10) stated that high temperature was desirable in composting. The optimum temperature ranges were found to be between 50 to 70°C. Wiley(11) reported that at temperatures from 50 to 60°C, a good compost was produced.

It was the opinion of many investigators that temperatures above 65°C resulted in decreased activity because only a few groups of thermophiles could live above this level.

Generally speaking, all investigators found that the maximum temperature of 60 to 70°C was reached in 2 to 3 days, and during this period most of the organic matter was consumed by microorganisms. The optimum temperature seemed debatable.

Michigan State University studies(8) on oxygen uptake indicated that maximum oxygen utilization was at 45°C, which indicated that most rapid decomposition took place at the 45°C level. Ludwig(30) also observed that optimum temperature was around the 45°C level.

7. Hydrogen-ion Concentration

Another factor which influences the composting process is the pH of the organic matter. The initial pH of organic waste such as garbage ranges from 5.0 to 7.0, unless the waste is high in ash or other alkaline material(10).

Gotaas(10) reported that an initial low pH value of 5.0 to 7.0 did not seriously retard the biological activity since active decomposition and high temperature developed rapidly after material was placed in the digester. However, the temperature did appear to increase a little more rapidly when the initial pH was in the range of 7.0.

According to Michigan State University studies(8), the change in pH during the composting process may be generalized as follows: Initial pH 5.0 to 6.0 with rapid decline to 4.0 or 5.0; a pH rise to 8.0 or above after second day; and finally a pH level of about 8.0 for the last stage of composting.

Wiley(11) and Michigan State University studies(8) showed a marked drop of pH on the first or second day of composting. This was probably due to the putrefaction of the organic material in the initial stages of decomposition.

B. OTHER FACTORS RELATED TO COMPOSTING

1. Time Required for Composting

Time required for satisfactory composting depends primarily on: a) particle size; b) moisture content; and c) aeration.

Windrow type composting has usually been accomplished in about 10 days, but has required longer periods when the three factors mentioned above were not controlled. The digester type composting process has seemed to produce compost more rapidly than windrows(8). Snell(6) obtained a fairly stable humus from the aerated digester after 3 to 5 days of composting. The Dano Process has reportedly obtained a fairly good compost after 3 to 5 days. Wiley(11) produced a good humus in 7 days of composting.

2. Testing and Judging the Process

Several tests have been used by Michigan State University(8) to determine the condition of material at various stages of composting. The tests were quantitative, and included: a) moisture; b) pH; c) per cent ash and volatile solids; d) temperature; and e) per cent nitrogen. Other quantitative tests which were used by Michigan State University included:

a) relative stability test; b) biological oxygen demand; c) chlorine demand; d) iodine demand; e) chemical oxygen demand; f) oxygen consumed test; g) oxidation-reduction potential; h) bacterial count; i) colorimeter; j) permeability; and k) fineness modulus(8,26).

Tests for odor and appearance have also been used in judging the process(8).

3. Weight-Volume Relationship

Several final ash contents have been reported by different investigators. The following table indicates the variations:

Table 1

Investigators	Material Used	Final Per Cent Ash
Wiley(11)	garbage and refuse	15
Turney(16)	garbage	23
Ludwig(30)	garbage	50
Gotaas(10)	garbage	20-65
McGauhey(5)	garbage and refuse	37
Anderson(19)	manure	20-56
New Zealand(20)	rubbish(no garbage)	51-63
California(12)	refuse	28.5

Final ash content probably depended upon type of material composted (garbage, refuse, sewage, sludge, etc.)

and upon the level of biological breakdown obtained.

Ludwig(30) observed that greatest volatile matter reduction of garbage was obtained at 40 and 45°C levels.

4. Free Air Space

Closely related to oxygen supply rates are the physical qualities of bulk density and porosity. Bulk density is defined as the dry weight divided by the original wet volume. Porosity and free air space are defined as:

$$\text{Porosity} = 1 - \frac{\text{Bulk Density}}{\text{Particle density}}$$

$$\text{Free air space} = \text{Porosity}\ (1 - \text{Moisture})$$

in which moisture is a decimal fraction. Free air space varies with porosity and moisture content. Table 2 illustrates the physical relationship of a finely ground garbage of 0.4 to 0.9 fineness modulus at various moisture levels:

Table 2

Relationship Between Per Cent Moisture and Free Air Space

Percent Moisture	Bulk Density	Porosity	Free Air Space
41	0.2830	75.5	44.5
50	0.2540	78.0	39.0
58	0.2443	78.9	33.8
64	0.2557	77.9	28.0
70	0.3070	73.4	22.0
Blank	------	----	----

5. Fineness Modulus

Batzer(26) observed that in a deck digester the volume of ground garbage in the holding tank tended to decrease. This decrease was due to: a) some of the material being dissolved; b) some of the fine particles packing together forming larger particles; and c) some of the fine particles being carried away by the water drainage from the tank. An increase in the per cent of fine particles which was observed as the material processed through the digester was explained being due to: a) biological activity; and b) abrasive action due to the rotating plows.

Fineness modulus was determined by dividing the weight of material retained on the number 60 sieve by the weight of material retained on the number 10 sieve. Batzer evaluated the Fineness Modulus as follows:

Table 3

Fineness Modulus of Initial and End Material

Initial	End
0.440	0.904
0.438	0.894
0.521	0.887
0.577	0.925
0.643	0.915

SECTION III

THEORETICAL CONSIDERATIONS

A. Temperature

Aerobic composting is brought about by living organisms which utilize carbon as a source of energy. During this process, carbon is burned and respired as carbon dioxide. Energy is liberated, and the amount of energy liberated varying with the degree of oxidation.

Heat liberated by the aerobic oxidation depends on the degree of oxidation which it undergoes; the more complete the oxidation the higher the energy level.

Glucose is often used for comparing the energy liberated during oxidation:

a. Complete aerobic oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6\,H_2O + 674 \text{ kilocalories}$$

b. Partial aerobic oxidation

$$2C_6H_2O_6 + 9O_2 \rightarrow 6C_2H_2O_4 + 6H_2O + 493 \text{ kilocalories}$$

1. Heat Conduction

Temperature of a composting material may be controlled by use of cooling coils. If water is used in the coils, the heat transfer from composting material to water is by conduction.

It is found experimentally that $\frac{H}{A}$, the rate of heat flow per unit area, is proportional to the temperature gradient, $\frac{\Delta T}{\Delta X}$. The proportionality constant is the coefficient of heat conduction K. Analytically, then,

$$\frac{H}{A} = K \frac{\Delta T}{\Delta X}$$

where K is in kilocalories/ sec m ^{o}C, H in kilocalories/ sec, ΔX in meters, A in square meters, and ΔT in ^{o}C. Then the rate of heat flow will be:

$$H = KA \frac{\Delta T}{\Delta X}$$

For copper coils having a K of 0.092, thickness of 0.001 meter, diameter of 0.005 meter, length of 1.0 meter, and temperature difference of 35^{o}C, the rate of heat flow becomes:

$$H = 101.5 \text{ kilocalories/ sec}$$

2. Amount of Cooling Water

The amount oc cooling water required to lower the temperature of composting material may be computed, using 674 kilocalories for complete oxidation of one gram of glucose:

$$Q = c\ m\ T$$

where Q is in kilocalories, c is specific heat of water (approximately 1.0), and ΔT is in ^{o}C, m is in kilogram.

m then becomes:

$$m = \frac{674}{\Delta T}$$

If the temperature change was 10 to 25°C the amount of water required would be 45 grams water per gram of glucose. Since organic material does not contain 100 per cent glucose, the amount estimated is more than enough to change the temperature level.

By trial and error, optimum water flow may be determined. The desirable water flow rate should be such that the cooling coil does not chill the material, and at the same time cool the material effectively during the peak digestion.

B. Oxygen Supply with Forced Air

In aerobic digestion of organic material, microorganisms utilize oxygen for biological combination with carbon of the organic material, and in the process produce carbon dioxide and water. A general expression for aerobic digestion of organic matter may be represented as follows:

$$C_x H_y O_z + bO_2 \rightarrow xCO_2 + \frac{y}{2} H_2O$$

In raw organic matter such as garbage, carbon, nitrogen, phosphorous, and potassium, which are essential to biological growth, are present in more than adequate amounts and present no problem(5,10,11,18,20).

1. Free Air Space

Ground garbage is a porous material with varying degree of free air space. The rate of air flow through a porous body is dependent upon the available free air space. The free air space in garbage is obtained from the expression:

$$\text{Free air space} = \text{Porosity}\ (1 - \text{moisture})$$

Moisture is expressed as a decimal fraction. Porosity, as used here, is the free space occupied by both the water and the air, and can be determined as:

$$\text{Porosity} = 1 - \frac{\text{Bulk Density}}{\text{Particle Density}}$$

where bulk density is the dry weight of the material divided by the orgininal volume wet material before drying. Particle density is 1.154, for garbage.

From above relationship, it follows that the amount of free air space depends on per cent moisture and porosity.

For garbage having 58 per cent moisture, bulk density 0.2308, particle density 1.154, and porosity of 80 per cent, the free air space is 33.6 per cent.

2. Air Distribution Through a Plastic Screen

When fluid flowing in a pipe is forced to undergo any change in velocity, there is a loss of head. At the entrance to a pipe line, at enlargement or contraction, the change in velocity entails losses which in some cases comprise a relatively large portion of the loss in head.

a. Sudden Enlargement

Head loss of a fluid through a sudden enlarged section may be determined by theoretical means. Initial flow has a cross sectional area A_1 and is discharged into a large pipe of cross sectional area A_2. Then the head loss may be found by Bodda's formula(32),

$$H_e = \frac{(V_1 - V_2)^2}{2g} \quad , \text{ or } H_e = \left[1 - \left(\frac{d_1}{d_2}\right)^2\right]^2 \frac{v_1{}^2}{2g}$$

b. Sudden Contraction

Similarly, head loss due to sudden contraction may be determined,

$$H_c = \left(\frac{1}{C_c} - 1 \right)^2 \frac{V^2}{2g}$$

where C_c is a coefficient of contraction.

When the air enters a chamber below the porous plastic false bottom, there is a head loss due to sudden enlargement, and as the air passes through openings in the plastic plate there is a head loss due to sudden contraction.

The total head loss due to sudden enlargement and sudden contraction is:

$$H = H_e + H_c = \left[1 - \left(\frac{d_1}{d_2}\right)^2\right]^2 \frac{V_1^2}{2g} + \left[\frac{1}{C_c} - 1\right]^2 n \frac{V_3^2}{2g}$$

If C_c 0.5 then, $$H = \left[1 - \left(\frac{d_1}{d_2}\right)^2\right]^2 \frac{V_1^2}{2g} + n \left(\frac{d_2}{d_3}\right)^2 \frac{V_2^2}{2g}$$

From above equation, head loss of a fluid before it reaches the compost may be calculated.

Head loss due to sudden enlargement is negligible compared to head loss due to contraction, therefore it may be stated that head loss in a system as described above is primarily due to fluid flowing through small openings.

More effective air distribution results from air flowing through a number of small openings than through several larger openings.

C. Moisture Balance

During aerobic oxidation of organic material, carbon dioxide and water are produced. The exact moisture content of inlet and exhaust air can be calculated or determined; however, the exact amount of water produced by aerobic breakdown can not be calculated mathematically due to varying degree of aerobic oxidation that takes place.

Therefore, moisture balance within a digester is extremely difficult. Best results to date have been obtained on a trial and error basis, adding necessary water in the form of saturated air when required.

SECTION IV

EXPERIMENTAL EQUIPMENT AND MATERIALS

A. Equipment

Laboratory equipments used in connection with these studies included the following: Cenco moisture balance, Precision Scientific Company oven, Volhand Speedigram balance, Beckman automatic titrator, Brooks flowmizer rotometer, Binks air pressure meter, General controls solenoid valve, Cutler hammer motor control, Haskings electric furnace, and meat grinder.

1. Basic Unit

Laboratory experiments were conducted in a specially built steel can used for ice cream shipment. The container measured $8\frac{1}{2}$ inches in diameter and was 21 inches high as shown in Figure 5. The unit had a working capacity of about 4 gallons. The openings at the top and bottom permitted the entrance and exit of air. The lower air pipe was located below a plastic plate and at the center of the bottom of the unit. The plastic plate was perforated with small $\frac{1}{64}$ inch diameter holes and was installed 3 inches above the bottom of the unit, serving as a false bottom.

The unit was covered with a steel top and then sealed with masking tape to make it air-tight. The unit was insulated with 2 inch fiber glass to prevent heat loss.

A drain for condensed liquor was provided at the bottom of the can with a small tube connected to a flask. The connection was gas tight and served to prevent an excessive build-up of moisture below the false bottom.

Inside the unit was a copper coil $\frac{1}{4}$ inch in diameter. One end was connected to a solenoid valve and the other open to the drain. A thermostat, located 7 inches above the plastic screen, was hooked up to the solenoid valve in such a way as to permit water flow in the copper tube when a temperature reached above the setting on the thermostat. A thermometer was inserted in the unit to record the temperature of the composting material.

2. Air Flow

Low pressure air, 5 psi, was provided through a pressure reducer and regulator, and was connected to an air flow meter as shown in Figures 5 and 6. The air was metered with a rotameter before passing through an air drying bulb which contained dry calcium chloride flakes, and then through an air heating chamber. The temperature of the air entering the unit at the bottom was maintained at the same level at which the experiment was run. Air was bubbled through water in the heating chamber to saturate it with moisture to the same temperature at which the experiment was conducted. Saturated air was used only when the moisture content of the composting material fell below a 52 per cent level. The exhaust air was

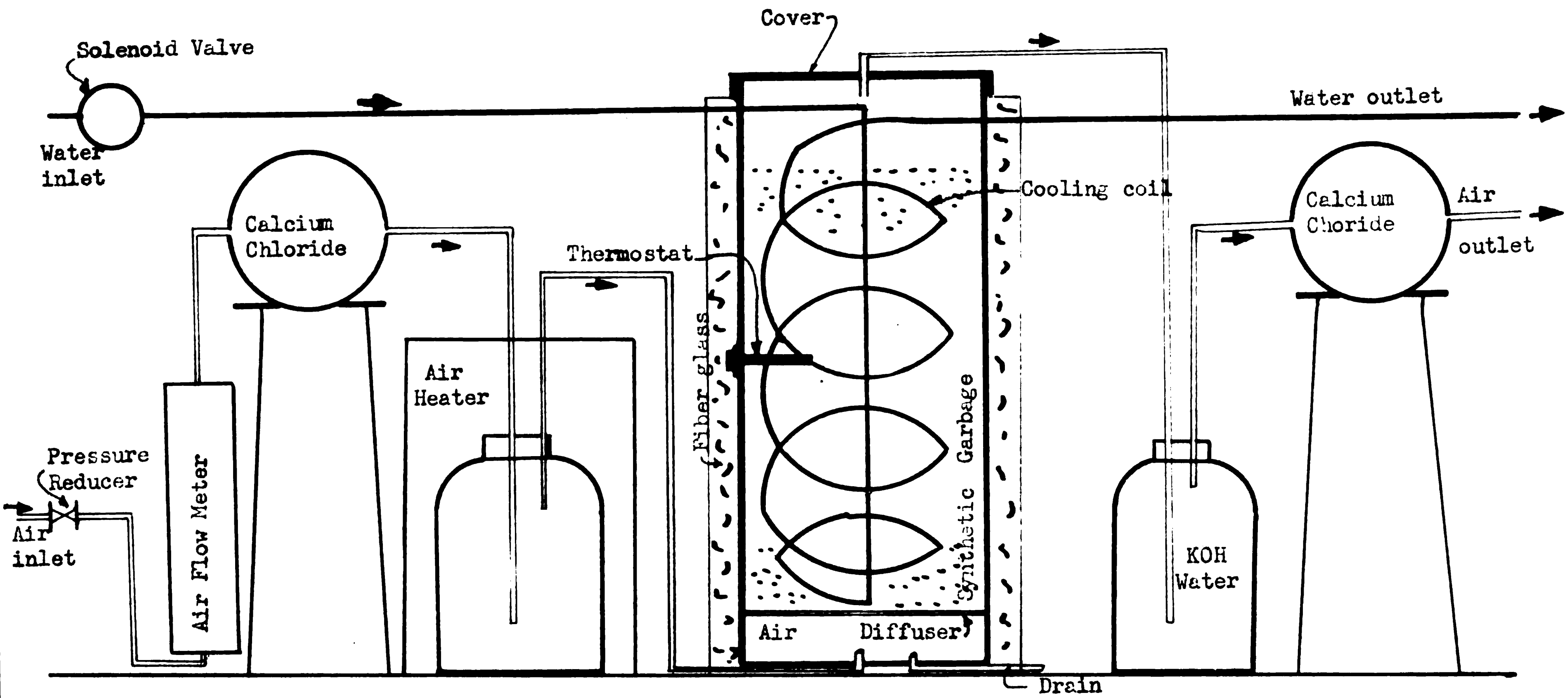


FIGURE-5: LABORATORY MODEL FOR CONTROLLED TEMPERATURE FORCED AIR COMPOSTING

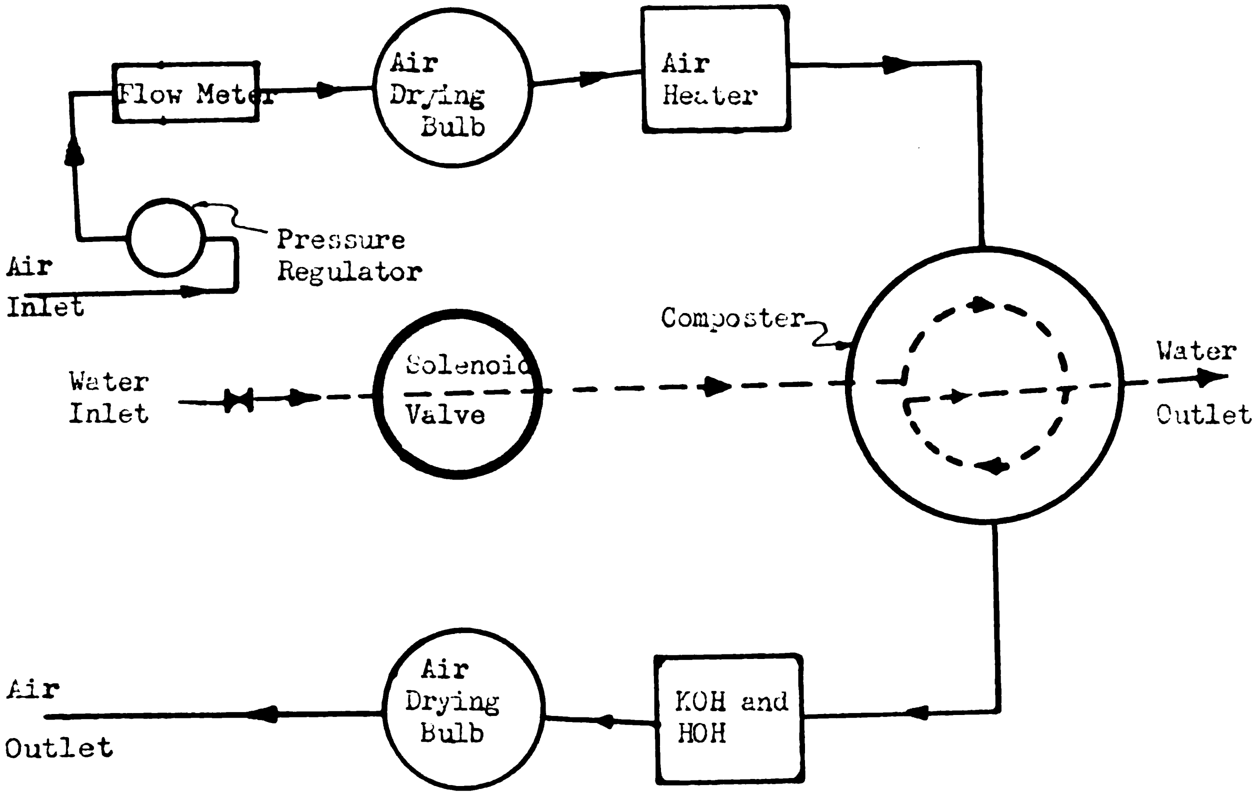


Figure - 6 : Air and Water Flow Sheet For CONTROLLED TEMPERATURE AND FORCED AIR COMPOSTING passed through a bottle containing potassium hydroxide and water to remove carbon dioxide, and then through a second air drying bulb before it was finally discharged into the atmosphere.

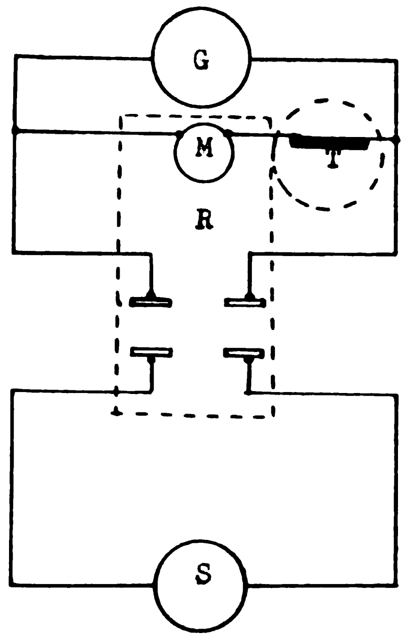
3. Use of the Solenoid Valve for Water Flow

The solenoid valve was used to control the flow of cooling water. Electrical connections of the solenoid valve, relays, and the thermostat are shown in Figure 7.

The thermostat was connected with the main circuit in series with the relay. The relay operated the solenoid valve. When the temperature of the composting material exceeded a set temperature, the thermostat circuit opened, causing the relay to close the solenoid valve circuit and permit water to flow as illustrated in Case B, Figure 7. As long as the temperature of the composting material remained below the set level, the solenoid valve remained open as illustrated in Case A, Figure 7, and no water could flow.

B. Raw Materials

The heterogeneous nature of garbage and the varying degree of decomposition which takes place at the time of collection introduces variables which can not be controlled. For this reason, reproducible samples can not be expected. Such difficulties were minimized in these studies by using freshly

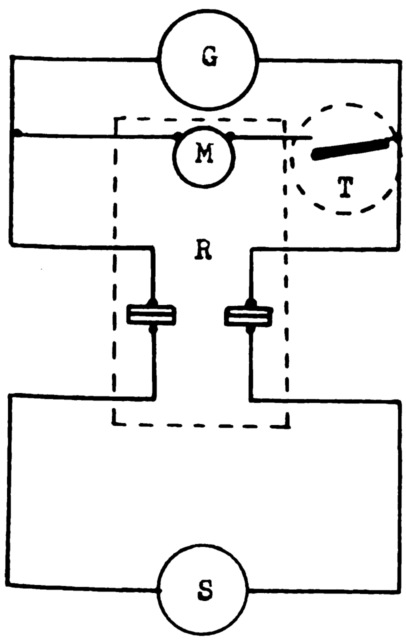


CASE - A

Symbols: G . . AC Generator
T . . Thermostat
R . . Relay
S . . Solenoid Valve
M . . Magnet

Case A

Solenoid valve closed.
No water flow.



CASE - B

Case B

Solenoid valve open.
Water flow.

FIGURE-7 : ELECTRICAL CONNECTIONS FOR SOLENOID VALVE ground vegetables, bread, potatoes, meat, fruits, coffee and tea grounds, and paper. By using a percentage of each constituent according to a garbage analysis made of East Lansing residential garbage, a good synthetic garbage was obtained.

The specific sonstituents of the synthetic garbage was that of garbage collected during 12 months of 1954 at East Lansing, Michigan, and analyzed by George Mallison of the Public Health Service. The constituents included the following:

Paper	Kraft and newsprints used for wrapping residential garbage
Meats	Meat and Fat
Citrus	Oranges and/or grapefruit, and/or lemons
Other Fruits	Bananas, tomatoes, apples, etc.
Green Vegetables	Lettuce and cabbage, etc.
Bread	Bread and pastry
Coffee and Tea Grounds	
Potatoes	

Table 4

Data on Specific Constituents of East Lansing, Michigan Residential Garbage

January to December 1954 — Average Values

Constituent Grouping	Per Cent Composition Wet Basis	Per Cent Solids	Dry Weights	Per Cent Composition Dry Basis	Per Cent Ash	Ash Weights	Per Cent Composition Ash Basis
Paper	18.63	69.0	12.85	37.6	1.6	0.206	21.9
Meat	7.92	75.6	5.99	17.6	0.8	0.048	5.1
Citrus	15.72	16.2	2.55	7.5	4.5	0.115	12.2
Other Fruit	7.55	14.4	1.09	3.2	7.6	0.083	8.8
Green Veg.	14.30	7.2	1.03	3.0	11.4	0.117	12.4
Coffee & Tea	4.38	36.2	1.09	4.7	1.8	0.029	3.1
Bread	9.85	66.4	6.54	19.2	2.7	0.177	18.8
Potatoes	13.01	18.8	2.45	7.2	6.8	0.167	17.7
Miscellaneous	8.64						

SECTION V

EXPERIMENTAL PROCEDURES and RESULTS

A. Method of Procedure

Methods of procedure for these studies were the same with one exception. In experiment 1, air added to the material was saturated with moisture at 40°C temperature level. In experiments 2,3,4, and 5, the air added was dried and heated to that level at which the experiments were conducted.

1. Insulation

Preliminary tests were performed to study the effect of insulation around the unit. The tests indicated that without insulation the temperature gradient in the material was very high. Maximum temperature gradient of 10°C was observed. However, tests with an insulated unit indicated heat loss was decreased and that the temperature gradient through the material was small. For this reason, throughout these studies the unit was insulated with 2 inches of fiber glass.

2. Ingredients

Predetermined amounts of freshly ground food were throughly mixed with finished compost before the mixed material was placed in the digestion unit. The percentage moisture content was approximately the same at the beginning of each run, being properly adjusted with oven-dry compost in each instance.

Each batch was sampled before the unit was charged with freshly mixed synthetic garbage. The quantity of synthetic garbage used in each run differed somewhat due to slightly different moisture contents but averaged about 13 pounds wet weight and 5 pounds dry weight. The intitial volume of the garbage in place was approximately 10,000 cc. The volume occupied by the composting material decreased during the decomposition. Generally, the percentage of finished compost used was 30 percent of the total dry weight of synthetic garbage.

3. Aeration Rates

Preliminary studies indicated that an aeration rate of less than 6 cu ft per hour often resulted in anaerobic conditions. On the other hand, an aeration rate above 6 cu ft per hour often resulted in excessive drying of the bottom portion of the material. A rate of 6 cu ft per hour per unit, or approximately 20 to 30 cu ft/day/lb of dry weight of material was used in all experiments.

Throughout the experiments, the temperature of the air entering the unit at the bottom was the same as that of the composting material.

4. Cooling Water Flow Rates

Several tests were performed to determine the optimum cooling water flow rate. It was observed that when the flow rate exceeded 45 ml per minute a rapid condensation took place around the coils and chilled the surrounding material. On the other hand, less than 45 ml per minute was insufficient to maintain a desired temperature level. Therefore, a water flow rate of 45 ml per minute was used throughout.

5. Determinations of Composting Material

The following determinations were made each day on the composting material: a) moisture content; b) pH; c) temperature; d) volatile solids.

6. End Product

Each test was concluded when the temperature of the composting material dropped rapidly toward the ambient temperature. At that time the top of the unit was removed, and the wet weight of the compost was noted. Samples were analyzed so that weights of various components could be calculated and compared with the initial values. The end product was well mixed and adjusted to the desired moisture level and placed in open cans for a re-heating test.

The re-heat in most instances was less than 10°C which seemed to indicate that the material was relatively stable. However, when the end product was mixed and reground, the temperature rise was more than 10°C.

Analysis of the end product included; moisture content, volatile solids, pH, temperature, bulk density, porosity, and free air space.

B. Sampling

Except for the initial and the final analysis, approximately 50 grams wet weight sample was taken each day from the unit for various determinations. Samples were taken from various depths in the unit; top, 4 inch depth, 8 inch depth, and bottom.

For initial and final bulk density determinations, 1000 cc of the material was taken out of the unit and oven dried. The weight of the material occupying 1000 cc varied with the final moisture content and degree of compaction.

Each day approximately 30 grams wet weight of the 50 gram sample of material was mixed throughly and the moisture determined.

Of the 50 gram sample, 5 grams were used for pH determination.

When the moisture determination was completed, the same samples were used for the volatile solids determinations.

C. Testing Procedure

1. Bulk Density, Porosity, and Free Air Space

Bulk density was determined twice, for initial and end product. The volume of material was determined by measuring the test unit volume and noting the relative volume occupied by the sample. Bulk density was defined as the dry weight divided by the original wet volume.

From the bulk density it was possible to determine the porosity of the material.

$$\text{Porosity} = 1 - \frac{\text{Bulk Density}}{\text{Particle Density}}$$

The particle density was previously determined by Shell(17) to be 1.154.

Free air space was computed by multiplying the porosity by one minus the moisture as a decimal fraction. Free air space was considered to be the free inter-connected air spaces through which the forced air could move to maintain aerobic conditions throughout the material.

2. Moisture

Three samples were collected each day for moisture determination. Moisture content was determined gravimetrically by drying in an oven for a minimum of 24 hours at 102 to 105°C.

$$\text{Per Cent Moisture} = 1 - \frac{\text{Dry Weight}}{\text{Wet Weight}}$$

A Cenco balance was used daily to check the moisture content of the material.

3. pH

Approximately 5 grams were placed in a flask containing 5 ml of distilled water. The pH of the material was read on a Beckman Automatic pH meter.

4. Volatile Solids

A test for volatile solids measures the amount of combustible matter lost on ashing. For determination of volatile solids, triplicate samples of dried material (generally 5 grams) were ashed at 650 to 700°C for at least two hours in a muffle furnace. Per cent volatile solids was computed on dry weight basis.

$$\text{Volatile solids} = 1 - \frac{\text{weight of ash}}{\text{weight of dry material}}$$

5. Temperature

The temperature of the composting material at various depths was measured daily with a thermometer. The temperature of inlet air was constant.

6. Aeration Rate

Aeration rates were measured with a rotameter which read mm of air per minute. As previously noted the rotamenter was on the inlet side of the experimental digestion unit.

7. Weight Balance

Attempts were made to determine the amount of CO_2 and H_2O produced. Carbon dioxide from the exhaust air was collected in a bottle containing 1758 grams KOH and 1000 ml water. CO_2 combines with KOH to form insoluble K_2CO_3 and water. Moisture from the inlet and exhaust air was collected in bulbs containing 3,000 grams dry calcium chloride.

D. Results

Summary of results for each experiment are shown in Tables 5 through 14.

Experiment 1: 40°C

This experiment was conducted at a 40°C level. The total dry weight of the intial material was 4.96 pounds, of which 2.3 pounds was oven-dried finished compost added as blending material. Air was supplied at 6 cu ft per minute and was saturated with moisture at 40°C.

Analysis for this experiment are shown in Tables 5 and 6. The temperature of the digesting material was maintained at 40°C level for 7 days. The temperature declined to within 5°C of ambient temperature at the end of 8 days.

The initial phase of composting was acidic with pH of 6.4, then pH rose to 7.2 on the first day. The pH continued to rise reaching 8.6 on the fifth day after which the pH declined slowly to 7.9 on the eighth day. No apparent decline in pH value was observed at the initial stage of decomposition.

Percentage values of moisture increased from 59.0 to 61.0 per cent. Volatile solids showed a decrease from 80.7 to 63.6 per cent. While percentage values appear to show little change during composting, the absolute weights showed a marked decrease. Losses in dry weight, especially for the volatile solids components, and total weight was significant. Per cent loss in volatile solids loss was 54.2 per cent, and total dry weight loss was 41.9 per cent.

There was slight decrease in free air space. The reduction of free air space was 2.4 per cent. Volume reduction was 48.3 per cent.

Table 5: Physical and Chemical Analysis of Compost At 40°C

Time (Day)	Unit Temp (°C)	Moisture %(WW)	Volatile Solids %(DW)	pH	Bulk Density (gms/cc)	Porosity (%)	Free Air Space (%)
0	40.0	59.0	80.7	6.4	0.235	79.6	32.6
1	40.5	59.4	78.8	7.2			
2	40.0	59.4	73.9	7.4			
3	40.0	59.5	72.3	8.0			
4	40.0	61.0	71.2	8.4			
5	40.5	59.8	68.0	8.6			
6	40.0	61.7	67.9	8.4			
7	40.5	62.0	64.5	8.1			
8	29.5	61.0	63.6	7.9	0.262	77.3	30.2
9	28.0	----	----	---	-----	----	----

Table 6: Weights and Losses in Composting Materials At 40°C

	Dry Weight				
	Volatile Solids	Ash	Total	Moisture	Total
Initial	4.00	0.96	4.96	7.14	12.10
Final	1.83	1.05	2.88	4.49	7.37
Loss	2.17	-0.09	2.08	2.65	4.73
% Loss	54.2	9.4	41.9	37.2	39.1

The experiment was concluded after 9 days. The temperature of the digested material remained at a 28°C level for 2 days. The end product appeared dark brown at 61 per cent moisture and light brown when dried.

An attempt was made to obtain a total weight balance, but the idea was abandoned due to inaccurate measurements of CO_2 and H_2O produced.

Experiment 2: 45°C

This experiment was conducted at a 45°C level. Total dry weight of the material was 5.28 pounds, of which 1.9 pounds was oven-dried blending material. The dry air was supplied at 6 cu ft per hour and at 45°C.

Analysis for this experiment are shown in Tables 7 and 8. The temperature of the digesting material remained at 45°C level for 6 days, then declined to 38°C on the seventh day, and to 30°C on the ninth day.

The initial phase of the digestion was acidic with pH of 5.6, and remained acidic until the second day. pH then increased rapidly to 8.5 and remained above 8.5 level for 3 days, after which, pH value declined to 8.0 on the ninth day.

The decrease in weight was somewhat less than in Experiment 1. Loss in volatile solids was 42.6 per cent and in total dry weight 34.5 per cent. A slight decrease of Free air space was observed. Volume reduction was 36.6 per cent.

The appearance of the end product was simillar in color and odor to that obtained in experiment 1.

Table 7: Physical and Chemical Analysis of Compost At 45°C

Time (Day)	Unit Temp (°C)	Moisture %(WW)	Volatile Solids %(DW)	pH	Bulk Density (gms/cc)	Porosity (%)	Free Air Space (%)
0	45.0	57.0	80.5	5.6	0.216	81.3	35.0
1	46.0	62.0	80.3	6.5			
2	45.0	60.6	79.7	8.5			
3	45.0	60.9	73.7	8.8			
4	45.0	57.5	73.5	8.7			
5	45.0	60.7	73.3	8.5			
6	45.0	58.8	73.3	8.3			
7	38.0	55.6	73.0	8.2			
8	32.0	58.3	70.3	8.1			
9	30.0	57.9	----	8.0	0.298	74.0	33.2

Table 8: Weights and Losses in Composting Materials At 45°C

	Dry Weight				
	Volatile Solids	Ash	Total	Moisture	Total
Initial	4.25	1.03	5.28	7.02	12.30
Final	2.44	1.02	3.46	4.85	8.31
Loss	1.81	.01	1.82	2.17	3.99
% Loss	42.6	9.7	34.5	30.9	32.4

Experiment 3: 50°C

This experiment was conducted at a 50°C level with a constant supply of 6 cu ft per hour of dry heated air at 50°C level. The total dry weight of the initial material was 6.48 pounds, of which 2.5 pounds was oven-dried finished compost used as blending.

Analysis for this experiment are shown in Tables 9 and 10. The temperature of the composting material remained at 50°C level for 7 days, then the temperature declined to 32.0°C on the eighth day and 29.0°C on the ninth day.

The initial phase of composting was acidic with pH of 6.8. Rapid decline of pH value was observed on the second day with pH of 5.2, and remained acidic until the sixth day. The pH then remained above 8.0 for 3 days.

Absolute reduction of total dry weight was 40.6 per cent and volatile matter 45.8 per cent. The reduction of Free air space was observed to be 3.2 per cent. Volume reduction was 39.5 per cent.

Experiment 4: 55°C

This experiment was performed at a 55°C level with a constant supply of 6 cu ft per hour of dry heated air at 55°C. The total dry weight of initial material was 7.22 pounds, of which 2.9 pounds was oven-dried blending material.

Analysis for this experiment are shown in Tables 11 and 12. The temperature of the composting material remained at 55°C level for 7 days, then the temperature declined to 36°C

Table 9: Physical and Chemical Analysis of Compost

At 50°C

Time (Day)	Unit Temp (°C)	Moisture %(WW)	Volatile Solids %(DW)	pH	Bulk Density (gms/cc)	Porosity (%)	Free Air Space (%)
0	50.0	55.0	85.6	6.8	0.223	80.6	36.2
1	49.0	59.0	84.2	5.4			
2	49.5	59.5	84.0	5.2			
3	50.0	58.8	83.7	5.3			
4	50.0	60.0	82.2	6.3			
5	50.0	58.3	81.0	6.7			
6	50.0	57.7	79.3	7.0			
7	50.0	54.9	79.2	8.3			
8	32.0	55.0	78.7	8.2			
9	29.0	56.3	78.4	8.0	0.283	75.5	33.0

Table 10: Weights and Losses in Composting Materials

At 50°C

	Dry Weight				
	Volatile Solids	Ash	Total	Moisture	Total
Initial	5.55	0.93	6.48	7.92	14.40
Final	3.01	0.84	3.85	4.95	8.80
Loss	2.54	0.09	2.63	2.97	5.60
% Loss	45.8	9.7	40.6	37.5	38.9

Table 11: Physical and Chemical Analysis of Compost At 55°C

Time (Day)	Unit Temp (°C)	Moisture %(WW)	Volatile Solids %(DW)	pH	Bulk Density (gms/cc)	Porosity (%)	Free Air Space (%)
0	55.0	56.0	82.9	6.7	0.219	81.0	35.6
1	55.0	57.5	82.3	6.0			
2	54.0	58.9	81.7	7.3			
3	54.0	58.5	81.4	7.6			
4	55.0	55.9	78.3	7.9			
5	55.0	54.5	77.0	8.1			
6	55.0	53.2	75.4	8.6			
7	55.0	52.4	74.9	8.3			
8	36.0	52.0	74.6	8.1			
9	24.0	52.5	74.5	7.9	0.313	72.9	34.6

Table 12: Weights and Losses in Composting Materials At 55°C

	Dry Weight				
	Volatile Solids	Ash	Total	Moisture	Total
Initial	5.98	1.24	7.22	9.18	16.40
Final	3.31	1.13	4.44	4.91	9.35
Loss	2.67	0.11	2.78	4.27	7.05
% Loss	44.6	8.87	30.3	46.5	43.0

on the eighth day and 24°C on the ninth day.

The initial phase of composting was acidic with pH of 6.7. The pH declined to 6.0 on the first day then rose continuously for 7 days after which pH leveled off.

Per cent moisture decreased from 56.0 to 52.5 per cent. Reduction of the absolute dry weight of the material was 30.3 per cent and volatile solids was 44.6 per cent. Free air space showed an increase of 1.0 per cent. Volume reduction was 28.1 per cent.

Experiment 5: 60°C

This experiment was conducted at 60°C level with a constant supply of dry heated air at 6 cu ft per hour at 60° level. The total dry weight of initial material was 5.76 pounds, of which 2.5 pounds was oven-dried finished compost used as blending.

Analysis for this experiment are shown in Tables 13 and 14. The temperature of composting material remained at 60°C level for 9 days, then declined to 38°C on the tenth day. The digesting material remained acidic for 5 days. On the sixth day, however, the pH was 7.9 and remained above 8.0 for 4 days.

The moisture content of the composting material decreased from 60.0 to 56.5 per cent. Total reduction of dry weight was 29.5 per cent and volatile solids was 34.2 per cent. Free air space showed a slight decrease, generally due to a reduction in porosity.

Table 13: Physical and Chemical Analysis of Compost At 60°C

Time (Day)	Unit Temp (°C)	Moisture %(WW)	Volatile Solids %(DW)	pH	Bulk Density (gms/cc)	Porosity (%)	Free Air Space (%)
0	60.0	60.0	88.0	6.7	0.248	78.5	31.4
1	50.5	60.0	87.7	5.8			
2	59.0	59.0	87.3	4.6			
3	60.0	59.3	87.3	4.8			
4	60.0	59.0	86.8	5.6			
5	60.0	58.9	85.8	5.9			
6	60.0	57.5	85.4	7.9			
7	60.0	57.2	85.1	8.3			
8	60.0	57.2	84.9	8.2			
9	60.0	56.9	84.6	8.1			
10	38.0	56.5	84.2	8.0	0.253	78.2	34.2

Table 14: Weights and Losses in Composting Materials At 60°c

	Dry Weight				
	Volatile Solids	Ash	Total	Moisture	Total
Initial	5.07	0.69	5.76	8.64	14.40
Final	3.34	0.62	3.96	5.14	9.10
Loss	1.73	0.07	1.70	3.50	5.30
% Loss	34.2	10.1	29.5	40.5	36.8

SECTION VI

DISCUSSION OF RESULTS

A summary of results from Controlled Temperature Forced Air Composting is plotted in Figures 8,9, and 10. The study indicated that an air supply of 20 to 29 cu ft/day/lb dry solids was adequate to maintain near-aerobic conditions when the moisture content of the composting material remained within 52 to 62 per cent levels. This range of aeration rates may be compared to previous studies on oxygen uptake made by Michigan State University(8) and by Ludwig(30). Michigan State University(8) reported a maximum air utilization of 18.1 cu ft/day/lb dry solids at $45^{o}C$ level with 56 per cent moisture. Ludwig(30) noted maximum air utilization to be 12 cu ft/day/lb dry solids.

Since the maximum utilization observed by the above workers were less than 20 cu ft/day/lb dry solids, it would seem that an aeration rate above this level would supply necessary oxygen to maintain near-aerobic conditions.

It was observed in this study that the moisture loss by forced air was not excessive to the extent as to cool or dehydrate the composting material. Braithwaite(9), in his barrel digester studies at Michigan State University, supplied 2 to 4 cu ft of air/day/lb dry solids. An air flow of 6 cu ft/day/lb dry solids was found to dry the composting material in the barrel at an excessively high rate, probably due to rapid evaporation during peak digestion.

Wiley(11) noted, in connection with garbage and refuse composting, that an aeration rate of 4 to 6.4 cu ft/day/lb volatile solids produced an incomplete product on the ninth day indicating lack of oxygen. On the other hand, with a higher rate of 33 to 78 cu ft/day/lb volatile solids, rapid cooling and dehydration of the compost was observed. With 10 to 30 cu ft/day/lb volatile solids, the end product seemed more stable than either at low or high aeration rates. An aeration rate of 10 to 30 cu ft/day/lb volatile solids would be 11 to 33 cu ft/day/lb of dry solids. Wiley's aeration range was broader than the rates used in this research.

Controlled temperature composting, as compared to an uncontrolled temperature process, gave a larger per cent reduction in volatile solids. A maximum volatile solids loss of 54.2 per cent was obtained at 40°C level, and the losses at other temperature levels were in the following order:

Temperature (°C)	40	45	50	55	60
Volatile Solids(%)	54.2	42.6	45.8	44.6	34.2

the volatile solids reductions at various temperature levels are shown in Figure 10-a.

From this it may be concluded that the normal 1 to 2 day period of initial temperature rise is not essential to good composting and that there may be material advantages in artificial heating of the material to avoid this lag period.

With garbage composting, Braithwaite(9) observed a maximum volatile solids reduction of 45 per cent. Wiley(11) noted a volatile solids loss of about 30 per cent in garbage and refuse composting. Volatile solids reduction of 54.2

per cent at 40°C was therefore greater than the values noted by other workers. A larger reduction at a 40°C level than 45°C was possibly due to mesophiles at optimum 40°C level. At a 45°C level, both mesophiles and thermophiles were probably present, the existance of one hindering the other.

A greater reduction of volatile solids at 40°C seemed to indicate maximum oxygen uptake at that level because organisms were more active and therefore utilized more oxygen. Michigan State University studies(8) indicated oxygen utilization in the following order, as shown in Figures 2 and 3: 45, 50, 55, 40, and 60°C. As has been stated, the volatile solids loss in this work were in the order: 40, 50, 55, 45, and 60°C. A remarkably close relationship exists between Michigan State University studies on oxygen uptake and the data reported here on volatile solids reduction, since the orders are identical except for interchange of positions for 40 and 45°C.

Gotaas(10) has stated that decomposition of organic matter proceeded at a rapid rate in a higher temperature range of 50 to 70°C and that these temperatures should be used in composting. While it is recognized that certain advantages are to be obtained on a practical basis with these higher temperatures it does appear that metabolism rates are higher in the mesophilic rather than in the thermophilic range. This fact raises the question as to whether the generally accepted use of high temperatures in composting should not be re-examined. More information is needed in this respect for it has not been established that a high rate of oxygen utilization and large reduction in volatile solids are necessary for good stabilization of these solid wastes. However, it is interesting to note that the end-products from this work did not reheat to any great degree after a second grinding and that most materials composted at higher temperatures have shown a capacity for reheating if ground and returned to the digestion unit.

pH curves for controlled temperature composting above 50°C follows the general pattern of curves obtained by Michigan State University(8), University of California(12), and Wiley(11). However, for the 40°C and 45°C levels no sharp decline in pH value was obtained. Absence of any sharp pH drop on the first and second day of digestion suggested that at lower temperature levels the condition of the material was more nearly aerobic. It should be noted that fresh food was used in all studies reported here.

Moisture contents of the digesting material were found to be at the levels of 52 to 62 per cent. By reversing the flow of air into the unit so that air entered at the top, much better control of moisture was possible.

Relationships between free air space and porosity of the material in the unit were established. The porosity was observed to decrease after a period of digestion. Initial porosity ranged from 78.5 to 81.3 per cent, and final from 72.9 to 78.2 per cent. Free air space in the material was governed by porosity and moisture content, the free air space being reduced by an increase in moisture content or by a reduction in porosity. Generally it was noted that both the per cent moisture and porosity decreased. No significant change in free air space was observed since changes in moisture content and porosity were such that the net change was small. Maximum variation in free air space noted was 2.8 per cent.

Use of a plastic screen such as that described in this study was effective in providing a uniform distribution of air into the unit without creating channels. As described in Section III, that uniform distribution of air was obtained by use of very small holes with resulting high head loss. Proof of the passage of air through the unit without channeling was provided by the uniformity of the finished compost which contained no pockets of partly finished material. The success of this technique indicates that turning and stirring may not be necessary in successful compost operations.

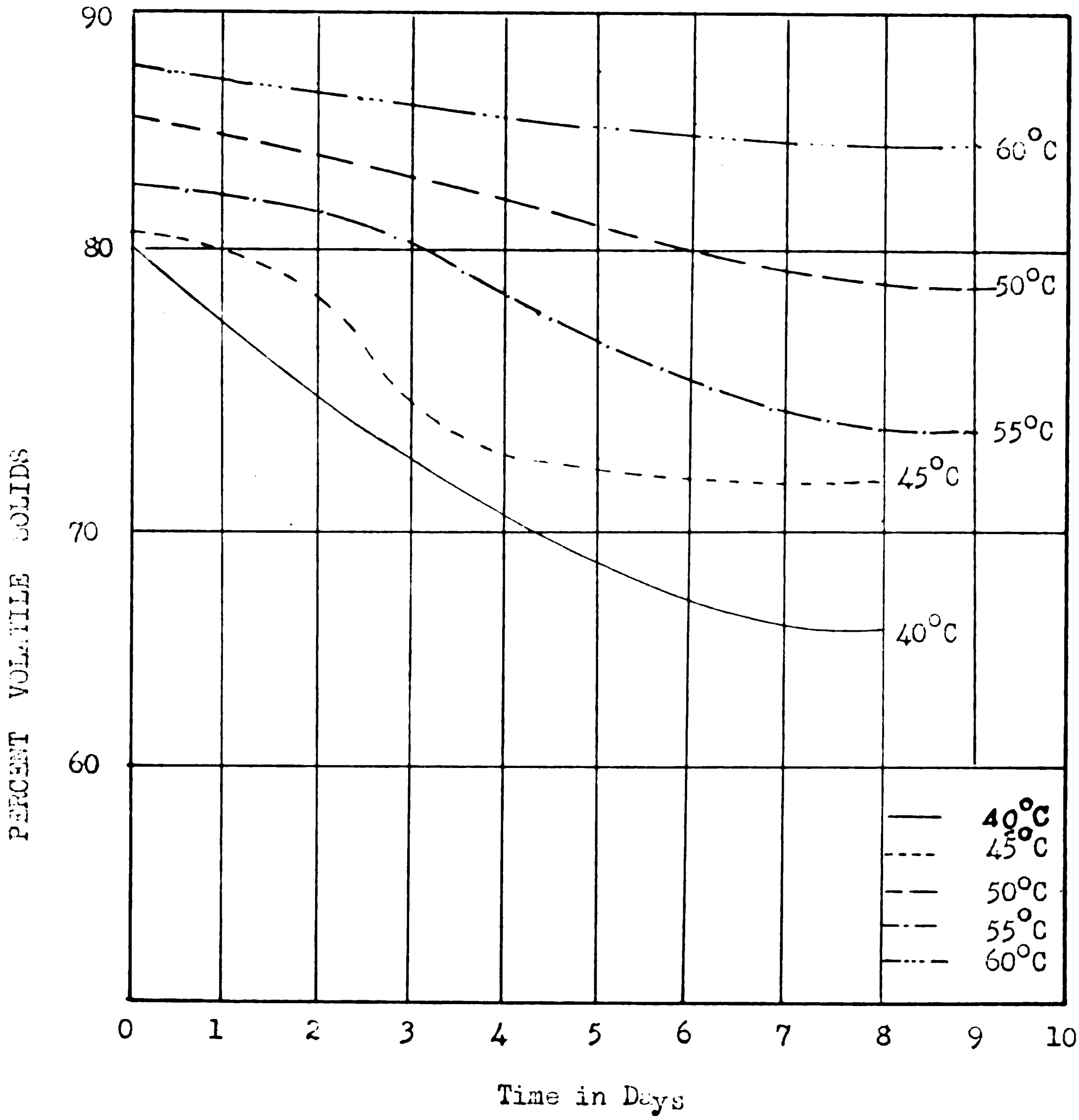


FIGURE - 8 THE RELATIONSHIP BETWEEN VOLATILE SOLIDS and TIME AT VARIOUS TEMPERATURE LEVELS

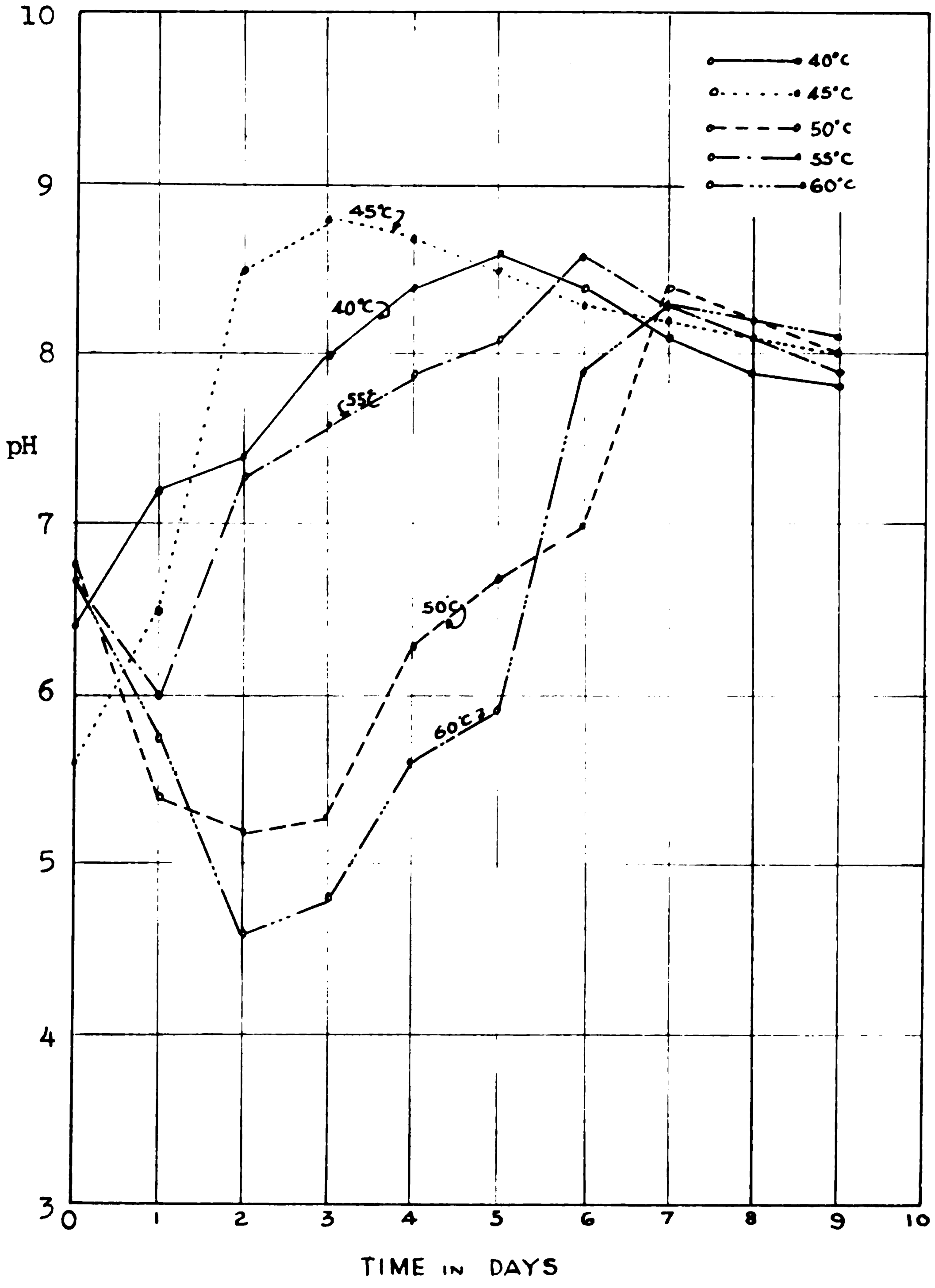


FIGURE --9: THE RELATIONSHIP BETWEEN pH and TEMPERATURE

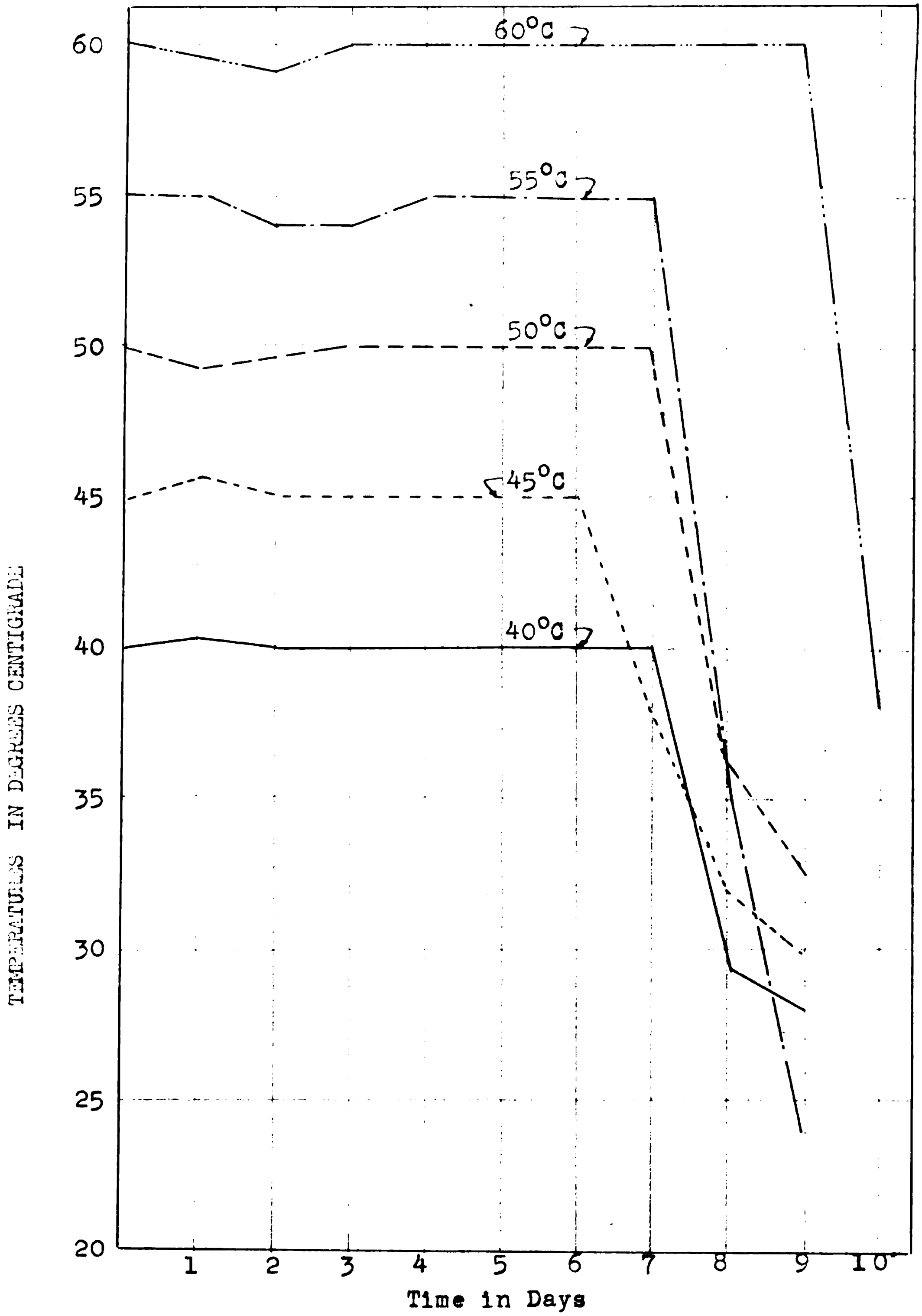


FIGURE--10: RELATIONSHIP BETWEEN TEMPERATURE AND TIME REQUIRED TO COMPOST

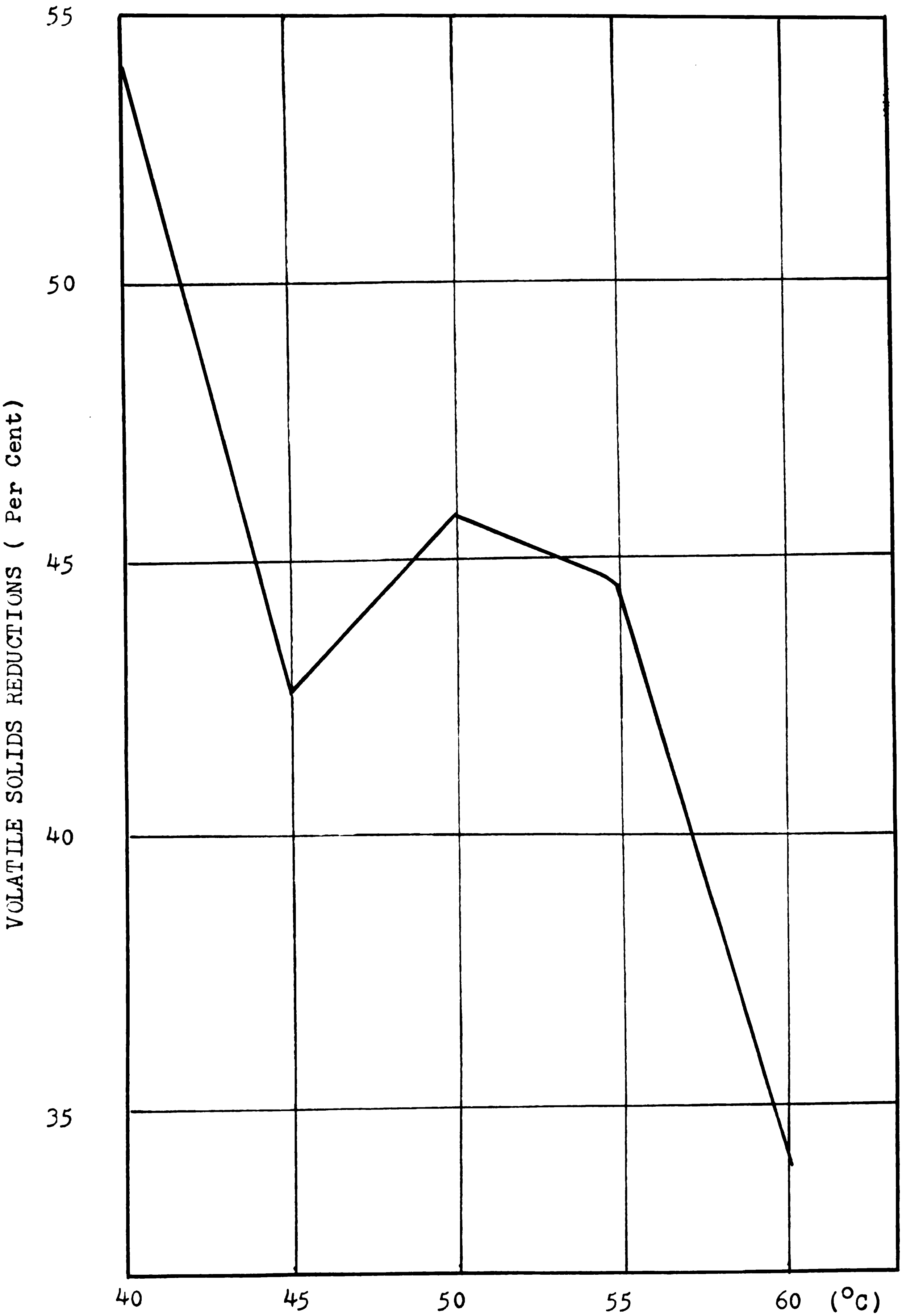


FIGURE 10-A: VOLATILE SOLIDS REDUCTIONS AT VARIOUS TEMPERATURE LEVELS

SECTION VII

CONCLUSION

1. Temperature of the composting material may be controlled to any desired level by means of cooling coils.
2. Under the conditions reported, an aeration rate of 20 to 29 cu ft of air per day per pound of dry weight of organic solids seemed sufficient to maintain near-aerobic condition during the composting.
3. Addition of saturated air to the digesting organic solids may not be desirable when the moisture content of the organic solids exceeds 60 per cent.
4. Supply of dry air from the top of a digester may be beneficial when the upper portion of the digesting material becomes excessively moist due to condensation.
5. Heated air showed no harmful effect and reduced lag period of initial temperature rise.
6. The reduction of volatile solids varied with temperature, and under tested conditions, the maximum reduction in volatile solids was observed at a 40°C level. The order of volatile solids reduction was: 40, 50, 55, 45, and 60°C.
7. A moisture content of 52 to 62 per cent was workable.
8. Porosity averaged 80.2 and decreased to 75.6 during composting. Per cent moisture decreased from 57.5 to 56.8. Free air space was reduced by the decreasing porosity and increased by the loss of moisture for an

over-all decrease of 1 to 3 per cent.

9. A porous plastic false bottom was found to be satisfactory for providing uniform distribution of the incoming air without channeling.

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