High Temperature Composting*

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Abstract

Composting temperatures of between 80 and 100°C have been demonstrated in laboratory and pilot plant studies with raw sewage sludge and domestic refuse mixtures. These high temperatures are the result of exothermic chemical reactions activated by biological heat generation. Coliforms, *Streptococcus faecalis, Clostridium perfringens* and ova of *Ascaris lumbricoides* did not survive high temperature composting for more than 240 hours in the middle zone of a pilot plant reactor. This is a significant improvement over the results obtained during windrow composting of digested sludge-refuse mixtures. The utilization of raw sewage sludge during high temperature composting eliminates the need for costly anaerobic sludge treatment and produces a valuable end-product free from pathogenic organisms for horticultural, agricultural, recreational and other uses.

Introduction

The increasing production of solid wastes with a high hygienic risk factor is one of the serious socio-economic problems confronting industrialized societies today. Digested sewage sludge and domestic refuse are important examples of such problematic wastes. However, the problem does not arise from a lack of technology, but mainly from economic considerations. Heat treatment, pasteurization, incineration with energy recovery and pyrolysis will effectively eliminate pathogenic organisms, but these disposal methods are relatively expensive. Consequently, these wastes are today mainly disposed of on land. Mechanized composting is practised in certain areas but is hampered by a lack of suitable market outlets and by the questionable hygienic quality of the end-product when sewage sludge is included and maturation periods are curtailed for economic reasons. Composting of domestic refuse alone has a lower hygienic risk factor, even in developing countries where the raw refuse may at times contain pathogens of faecal origin (Chinese Academy of Medical Science, 1975). In the Western Cape where a suitable market exists for the end-product (Lombard, 1976), mechanized composting has found application, but as yet only one composting plant adds sewage sludge to its refuse. If the pasteurization effect of composting can be enhanced, sludge can be used to a greater extent in the Western Cape. This not only makes use of the fertilizing value of the sludge, it also solves the problem of its ultimate disposal. If, in addition, dewatered raw sewage sludge is mixed with the refuse instead of digested sewage sludge, costly sludge treatment at the sewage works can possibly be avoided.

It is, therefore, obvious that more effective reduction in the numbers of pathogenic organisms during composting will have many benefits. To improve the pasteurization effect, either the time or temperature component during composting must be increased. Increasing the time component means longer maturation periods and, therefore, the ground surface needed for maturation must be enlarged. A lack of available ground or the high cost of land in urban areas normally makes this impossible. During windrow composting of refuse-sludge mixtures in the Western Cape, maximum temperatures of up to 65°C are generally observed with an absolute maximum of 72°C being recorded once by this Institute. Temperatures of 80°C and even higher have been reported (Schulze, 1965; Spohn, 1972) and Finstein and Morris (1975) concluded that chemical reactions probably contributed to the attainment of such temperatures. A temperature of 76°C is generally regarded as the maximum for thermophilic organisms (Rothbaum, 1961). The work of Rothbaum (1963) and Dye and Rothbaum (1964) has shown that temperatures above those attributable to biological action can be reached through exothermic chemical reactions in wool and hay. To obtain these high temperatures, which could eventually lead to spontaneous combustion, two requirements must be met. Firstly, the relative humidity in the interstitial spaces must be between 94 and 98% and 95 and 97% for wool and hay respectively. Secondly, certain chemical substances must be pre-

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sent that will initiate exothermic reactions leading to high temperatures. The nature of these substances has not yet been clarified. Browne (1933) suggested that micro-organisms will dehydrate sugars to unsaturated intermediate products which can then be oxidized with liberation of heat in the presence of air. Oxidation of poly-unsaturated oils in fish meal has also been identified as the cause of self-heating to combustion temperatures (FIRI, 1961). Firth and Stuckey (1947) were of the opinion that the decomposition products of the mesophilic stage are sufficient to catalyse further chemical carbohydrate decomposition leading to higher temperatures. While conceding that unsaturated hydrocarbons, whether initially present in the raw materials or being formed as intermediate products, probably are very important for chemical heat generation, Wiechers (1975) suggested that the reaction between nitrates and organic substances at thermophilic temperatures may supply sufficient heat to raise the temperature to 80°C. Nitrification during the early stages of composting was, therefore, regarded as essential.

This report deals with some of the results of a study conducted to establish the conditions necessary for high temperature composting (HTC) at 80°C or higher. For this purpose an adiabatic oil bath had to be designed and constructed to enable relatively small quantities of compost to self-heat under laboratory conditions. Based on the results of these laboratory investigations, a 5 m^3 pilot plant was constructed for evaluation of the process on a more realistic scale. Both these composting units provided for high temperatures by minimizing the loss of heat generated by biological means, thereby causing higher temperatures that could activate exothermic chemical reactions.

Materials and Methods

Adiabatic apparatus

The design of the adiabatic oil bath (Nell *et al.*, 1976) included a well insulated (75 mm glass fibre) galvanized steel bath in which was suspended a Pyrex glass reactor of 3 *l* capacity (Figure 1). This reactor was immersed in low viscosity transformer oil with low electrical conduction properties. It was fitted with a ground glass sealed lid with four openings. The first allowed the entry of air, the second the exit of exhaust gases. The compost temperature probe passed through the third opening, while the fourth was used as a sampling port. A centrifugal pump displaced the 30 *l* of oil in the bath in approximately 45 seconds. Oil leaving the pump first passed through a cooling unit to remove the heat generated by friction in the pump. From the cooler the oil flowed through a heating unit with a 2 kW capacity and then re-entered the bath through four nozzles.

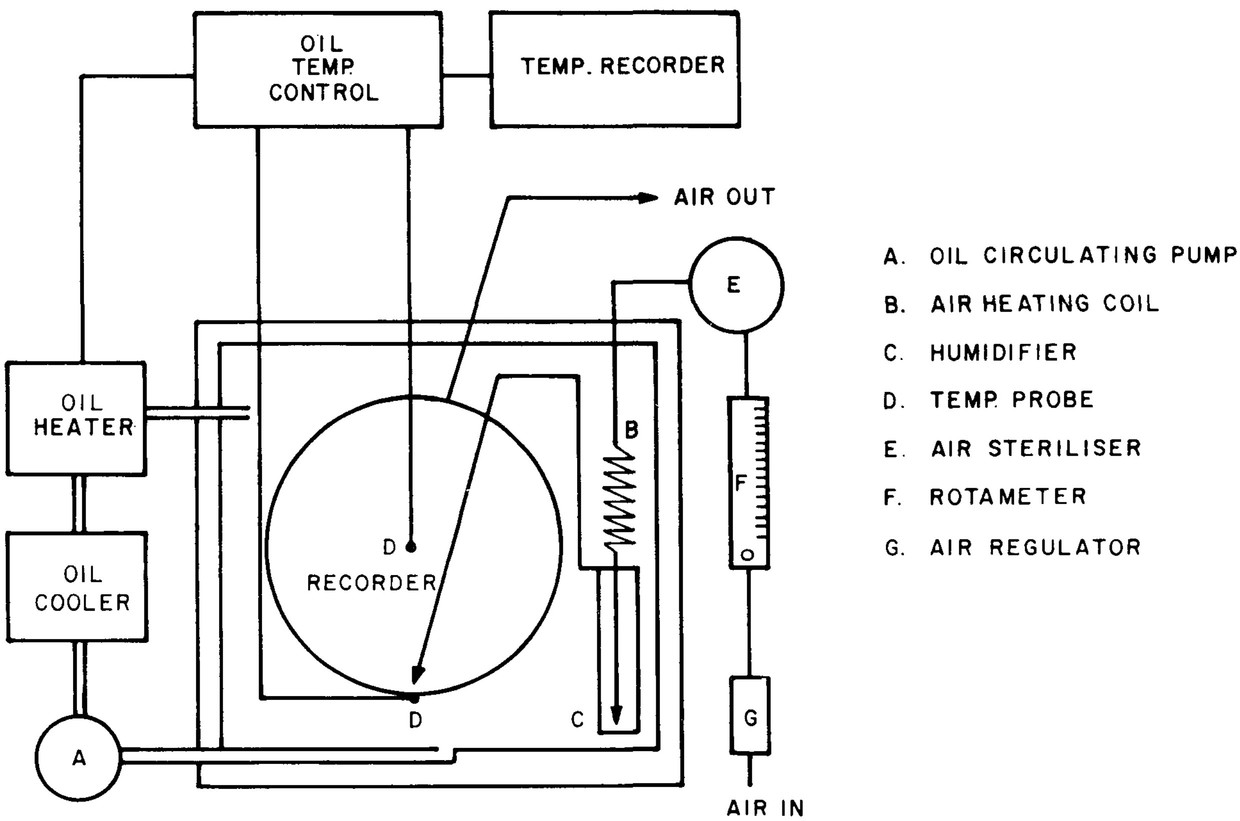

Figure 1
Schematic diagram of adiabatic oil bath

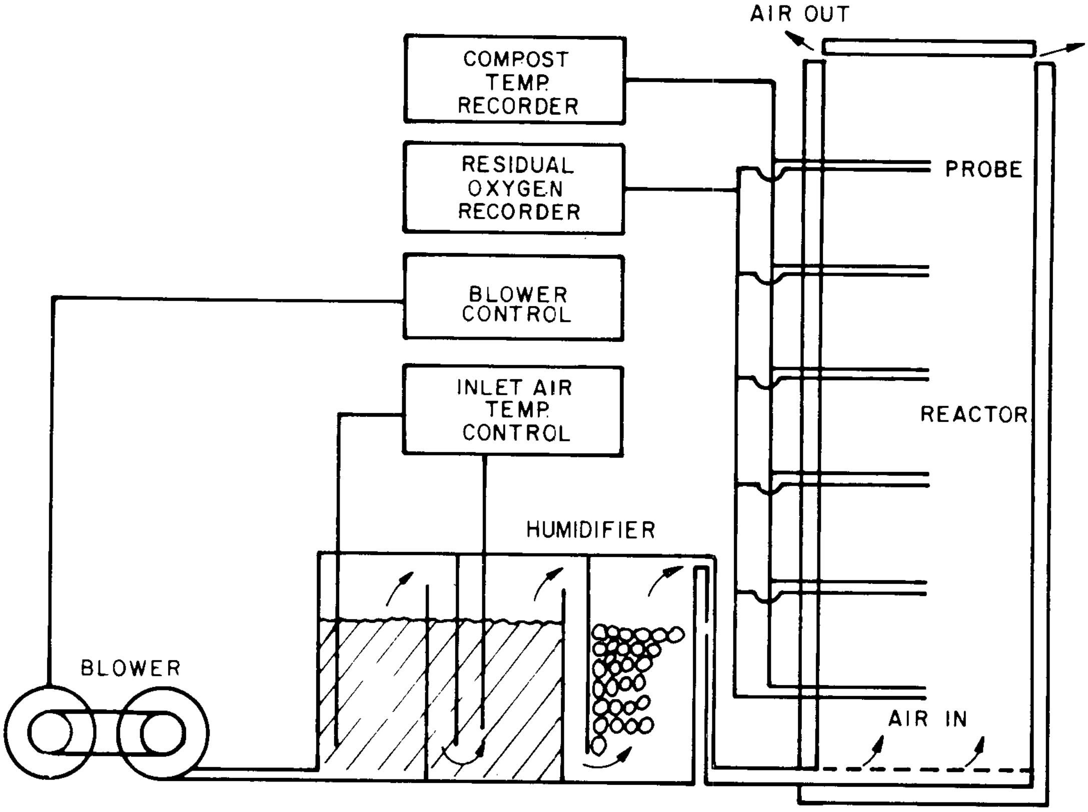

Figure 2
Schematic diagram of pilot plant

An electronic control system sensed the temperature in the compost and oil by means of closely matched transistors, of which the variation in the base to emitter voltage with respect to temperature was very closely linear. If the temperature of the compost increased by 0,2°C above that of the oil, the heating unit was activated until oil temperature equaled compost temperature. This differential control mode of operation ensured that the oil temperature followed the compost temperature closely, minimizing heat losses from the reactor. In addition to this differentially controlled mode of operation, the design of the adiabatic bath also provided for operation at set temperatures, should it be necessary to keep the temperature constant or to raise the heat level of the contents of the reactor to a higher constant value.

Air to the unit was first passed through a rotameter and a 0,22 μm Millipore sterilizer. From there it went through a heating coil and three Dreschel type humidifiers before entering the reactor with a relative humidity of 95%. Heating and air humidification were required to prevent heat losses through evaporation and convection.

Oil temperature was continuously recorded on a Jumo instrument. In addition to temperature measurements, the oxygen and carbon dioxide concentrations in the exhaust gas were determined by means of absorption type Fyrite instruments when required.

Pilot Plant

The steel reactor had a capacity of 5 m^3 and was insulated with a 75 mm thick layer of mineral wool (Figure 2). Six sampling points were distributed at regular intervals along the side of the reactor. Through these sampling holes removable aluminium probes were inserted which allowed the extraction of air from the middle of the reactor for analysis on a Beckman oxygen meter with recorder. Thermocouples were also inserted through the sampling holes to allow the temperature of the compost to be recorded continuously at all six points on a Honeywell instrument.

Air was supplied to the bottom of the reactor by two Rootes type blowers in series controlled by a time switch. Air from the blower passed through an insulated humidifier divided into three compartments. Each compartment contained a layer of Raschig rings at the bottom, while the first two compartments were also equipped with heating elements and were filled with water. The first two compartments, therefore, heated and humidified (95% relative humidity) the air, while the last removed excess moisture. Air temperature was controlled by regulating the water temperature in the first two compartments. Air temperature was always kept at approximately 5°C below the average temperature of the bottom four sampling points except when the compost had to be heated to eliminate the mesophilic stage. Heating and humidification of inlet air was used to prevent heat loss through convection and evaporation.

Analytical Methods

Residual oxygen concentration in both the laboratory adiabatic bath and pilot plant was regulated between 10 and 15%. Kjeldahl-nitrogen, pH and organic matter were measured according to the methods of the EAWAG (1970), while ammonia-nitrogen

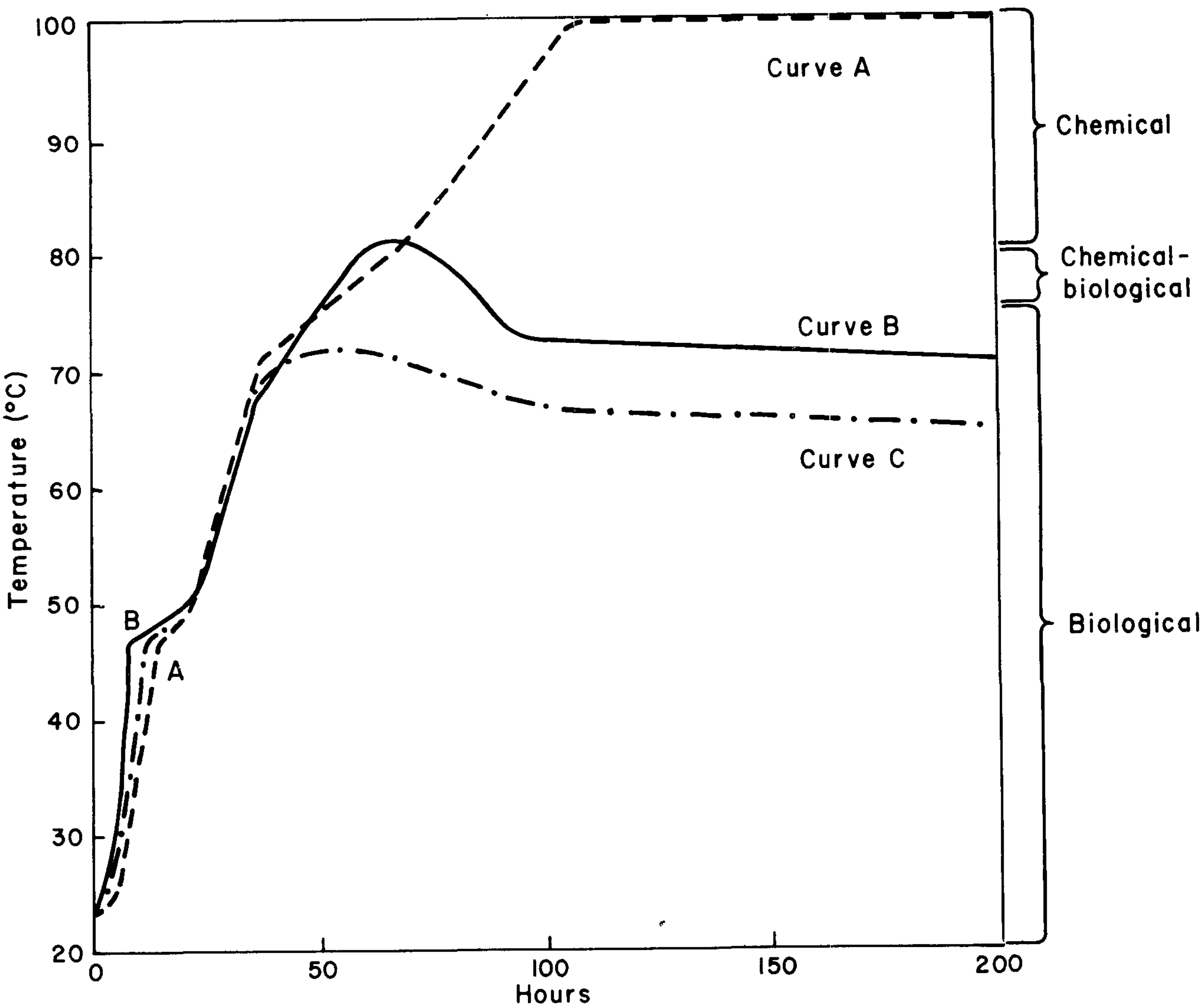

Figure 3
Three types of reference temperature curves obtained with adiabatic oil bath (Test No 1)

TABLE 1
SEVEN HEATING PHASES THAT CAN BE DISTINGUISHED DURING THE SELF-HEATING OF A 3:1 REFUSE-SLUDGE MIXTURE TO 100°C IN THE ADIABATIC OIL BATH

Phase	Temp. Range (°C)	Duration (h)	Rate of Temp. Increase (°C/h)
1. Mesophilic Lag Phase (MLP)	23 – 25	5	0,4
2. Mesophilic Accelerated Phase (MAP)	25 – 47	11	2,0
3. Thermophilic Lag Phase (TLP)	47 – 49	6	0,3
4. Thermophilic Accelerated Phase (TAP)	49 – 71	18	1,2
5. Hyperphilic Lag Phase (HLP)	71 – 80	30	0,3
6. Hyperphilic Accelerated Phase (HAP)	80 – 100	40	0,5
7. Isothermic Phase (IP)	100	70+	0

and nitrate-nitrogen were determined by methods developed in the Bellville Regional Laboratory of the CSIR. Microbiological analyses were performed according to the methods of the National Institute for Water Research (1973).

Experimental Procedures

All of the 22 laboratory-scale and 3 pilot-scale runs completed so far, except those where the sludge concentration was varied, contained on a dry basis 75% milled domestic refuse from the Bellville municipal composting plant and 25% dewatered sludge of which three quarters of the solids were derived from raw sewage sludge and one quarter from nitrifying activated sludge. Both sludges were dewatered by means of a centrifuge. To this mixture 5% (wet basis) of maturing windrow compost and 5% (wet basis) of the end-product from a previous run was added as additional thermophilic and nitrifying inoculants respectively. To enhance nitrification 0,1% (wet basis) of lime was added which resulted in an initial pH of approximately 7,5. This mixture (moisture content 50%) was then kneaded in a modified concrete mixer for at least 15 min and left for 5 h at temperatures between 15 and 20°C while residual oxygen concentrations were maintained between 10 and 15%. This treatment resulted in the formation of approximately 400 mg/kg of nitrates with a concomitant decrease in pH to approximately 6,5. The compost was then introduced into the adiabatic bath or pilot plant as required.

The following laboratory-scale results are reported:

Test 1: Six runs to establish a reference heating curve.

Test 2: The effect of the addition of poly-unsaturated fish oil (4% on a dry mass basis) with an iodine number of 190 on the temperature curve.

Test 3: The effect of different raw and digested sewage sludge concentrations on the temperature curve.

Test 4: The effect of eliminating the mesophilic stage of composting by raising the temperature immediately after start-up to 55°C.

Test 5: The effect of the addition of 0,5% nitrogen (dry basis) in the form of ammonia-nitrogen (ammonium acetate) and nitrate nitrogen (potassium nitrate) on the temperature curve.

Results obtained during the third pilot plant run with mesophilic stage elimination are reported as Test 6.

Results and Discussion

Test 1

The three types of temperature curves obtained during Test 1 are shown in Figure 3. Curve A (average of three runs) shows that heat was generated in seven distinct phases (Table 1). During the Mesophilic Lag Phase (MLP) the temperature increased from ambient to 25°C at a rate of approximately 0,4°C/h. This phase represents the stage of gradual adaptation for growth of mesophilic organisms. It was followed by a stage of rapid increase in temperature (2°C/h) during which time mesophilic organisms proliferated at the fastest rate. This is termed the Mesophilic Accelerated Phase (MAP) and ranged from 25 to 47°C. Mesophilic organisms then started to decline, while their thermophilic counterparts entered a period of adaptation and the temperature increased at a slow rate of about 0,3°C/h up to 49°C (Thermophilic Lag Phase, TLP). Once the thermophilic organisms were growing at the maximum rate, the temperature increased from 49 to 71°C at a rate of 1,2°C/h and this stage is therefore called the Thermophilic Accelerated Phase (TAP). These phases of lagging and accelerated growth of micro-organisms are known (Lamana and Malette, 1959) but it is believed that the temperature curves generated during these stages have been demonstrated for the first time by means of adiabatic self-heating.

Above 71°C the temperature curve entered another lag phase, termed the Hyperphilic Lag Phase (HLP), although it was not so markedly defined as the MLP and TLP. The HLP ranged between 71 and 80°C and probably represented a decline in the thermophilic organism population. The rate of temperature increase fell to 0,3°C/h during this phase which lasted for approximately 30 h. Before the thermophilic organisms ceased activity completely, another heat generating system was activated (Hyperphilic Accelerated Phase, HAP), which caused the temperature to rise at a rate of 0,5°C/h until 100°C was reached. This occurred approximately 110h after start-up. The temperature of the refuse-sludge mixture did not rise above 100°C during the following 70 h. All the energy produced in the reactor was probably absorbed as latent heat during the boiling of moisture in the reactor contents. This phase is tentatively referred to as the Isothermic Phase (IP).

Curve B represents the average of two very similar runs. During these runs the temperature entered the HAP, but insufficient heat was available to increase the temperature to the IP or even to maintain the temperature above 80°C for longer than 10 h. Curve C (one run only) shows a maximum temperature of only 72°C and probably represents a typical biologically generated temperature curve.

The reasons for the failure of certain runs to generate sufficient heat by chemical means to increase the temperature to the IP are uncertain, but three potentially contributing factors can be mentioned. Firstly, chemical substances capable of heat generation may have been absent altogether or were present in insufficient quantities. Secondly, these substances may have been present in adequate quantities but were initially utilized by mesophilic organisms as is indicated by the greater mesophilic temperature generation rates of curves B and C. In the third place, the relative humidity in the interstitial spaces of the different composts could have contributed to different results.

During later investigation it became clear that temperature curves such as type B are generally obtained using a 1:4 raw sludge-refuse mixture (50% moisture) with types A and C the exceptions. Since type B curves exceeded the originally stipulated minimum peak temperature of 80°C, it was accepted as the reference curve for comparison with the results of further investigations.

Test 2

This test involved the injection of poly-unsaturated fish oil with a known chemical heat generation capability into compost during a run which failed to maintain a positive temperature increase during the HAP. (Figure 4). The temperature curve of the test run followed the reference curve reasonably well during the first 90 h. Compost temperature was then increased to 86°C and held at that level for 16 h to activate chemical heat genera-

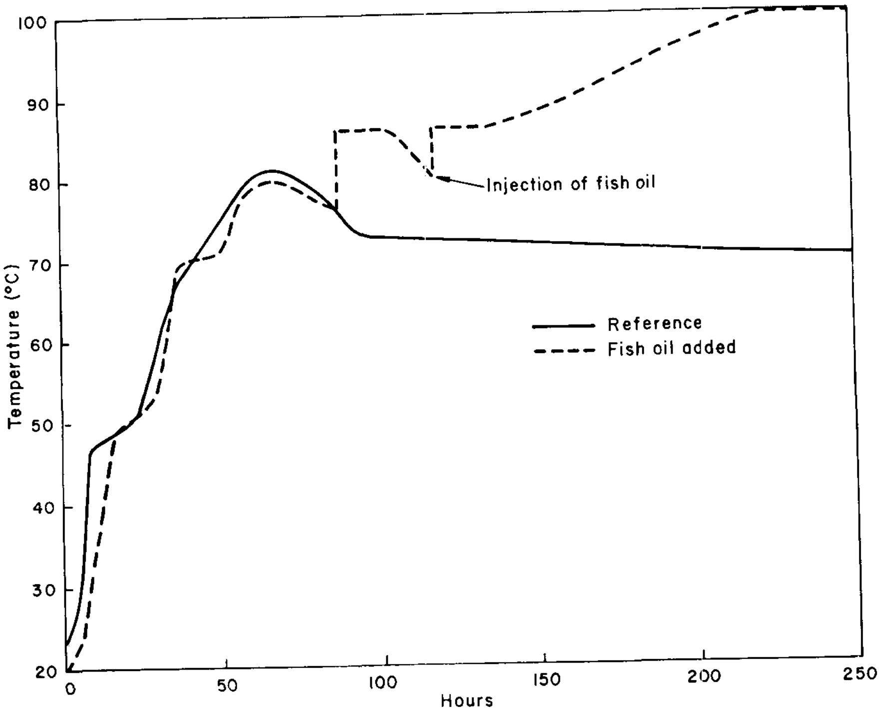

Figure 4
Effect of the addition of fish oil (4 percent on dry mass basis) on temperature curve (Test No 2)

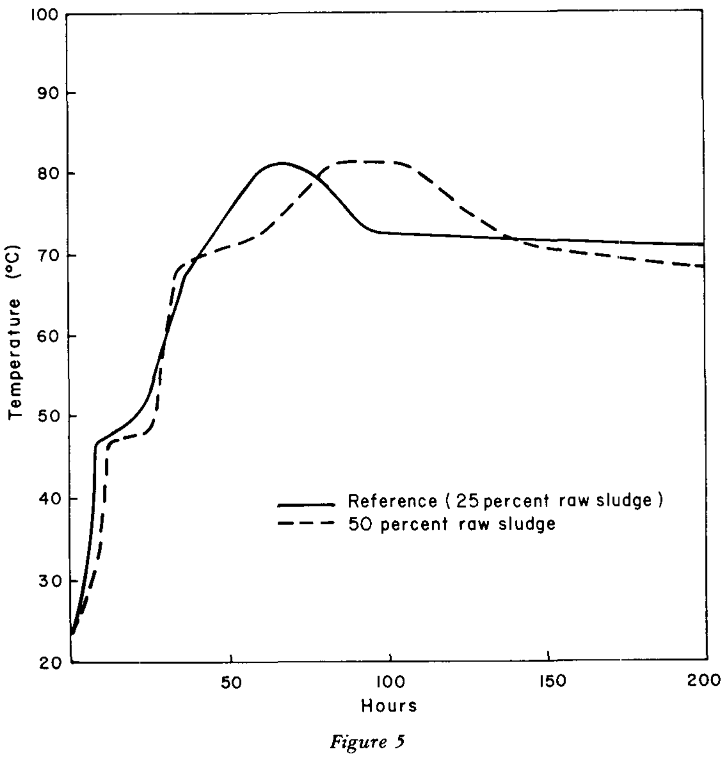

Figure 5
Effect of concentration of raw sewage sludge on temperature curve (Test No 3)

tion. Subsequent switching to the differential control mode caused a decrease in temperature. Fish oil was then injected (4% on a dry mass basis) and the temperature again increased to 86°C for 16 h. When switched to differential control, the compost started self-heating and the temperature reached 100°C after 90 h of differential mode operation.

Test 3

Test 3 was conducted to establish whether higher raw sludge concentrations would increase the concentration of chemical heat generating substances to such an extent that self-heating will cause the temperature to approach 100°C. Figure 5 shows

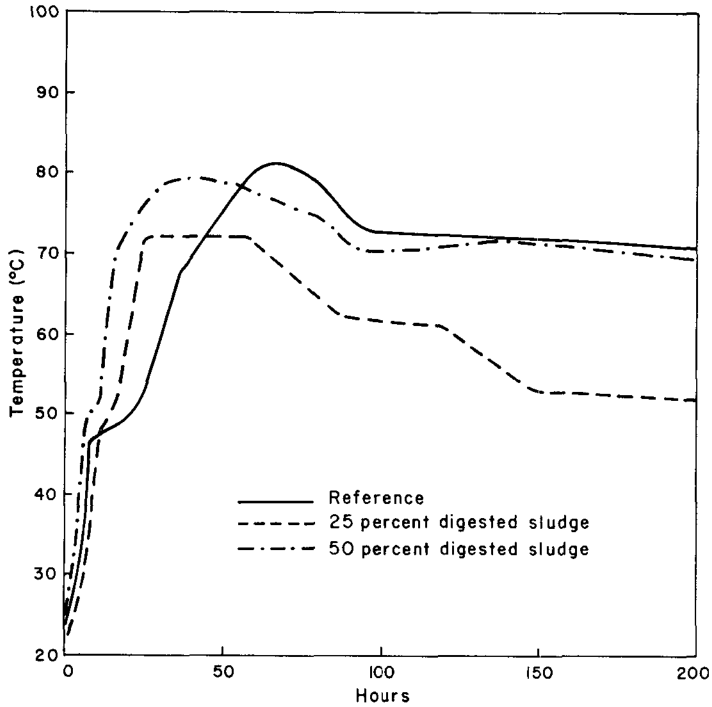

Figure 6
Effect of concentration of digested sewage sludge on temperature curve (Test No 3)

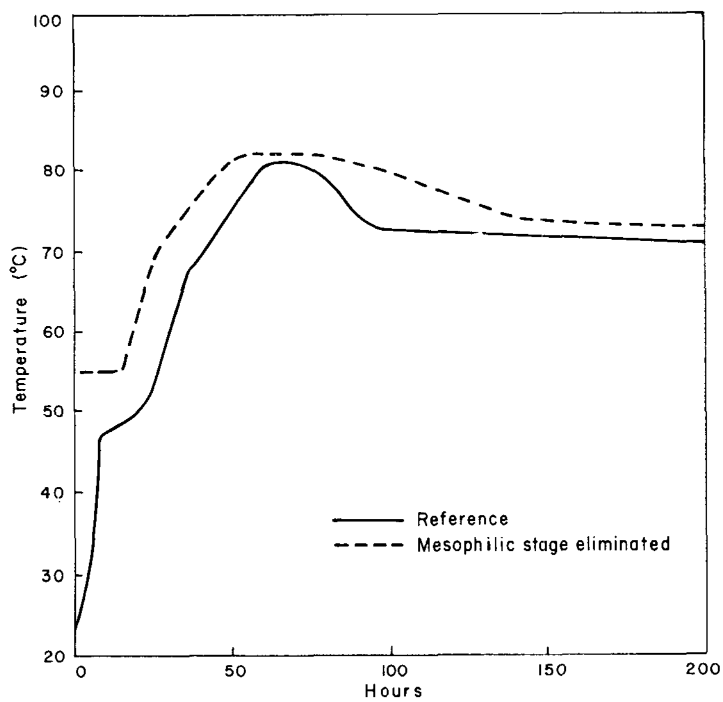

Figure 7
Effect of the elimination of mesophilic stage on temperature curve (Test No 4)

that a 50% raw sludge concentration had no beneficial effect on the temperature curve.

The experiment was subsequently repeated with dewatered digested sewage sludge (Figure 6). A compost mixture containing 50% digested sludge improved heat generation considerably in respect of both heat generation rate and maximum temperature, but both runs had maximum temperatures lower than that of the reference curve. It is, therefore, apparent that the use of raw sludge as opposed to digested sludge, holds a distinct advantage in respect of heat generation.

Test 4

The results of test 1 showed that the higher heat generation rates during the MAP of curves B and C were associated with lower maximum temperatures as compared with curve A. During test

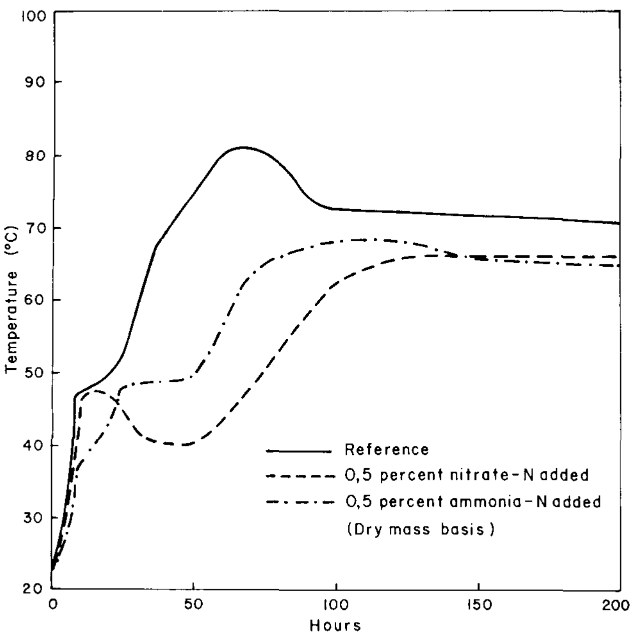

Figure 8
Effect of the addition of nitrate and ammonia nitrogen on temperature curve (Test 5)

4 the effect of elimination of the mesophilic stage was investigated by raising the temperature of the compost immediately after start-up to 55°C. Results given in Figure 7 show that this treatment resulted in the compost being heated much more quickly to reach a maximum temperature of 82°C after only 56 h. These results were later confirmed by pilot plant studies. The reason for this phenomenon is probably the provision of more substrate for the thermophilic organisms by eliminating mesophilic proliferation. It is also possible that substances capable of chemical heat generation may be carried over to the thermophilic stage where they may cause hyperphilic temperatures to be reached.

Test 5

The possibility of chemical heat generation by the reaction between nitrates and organic matter has been mentioned. Test 5 was, therefore, conducted to investigate the effect of increasing the nitrate-nitrogen content of the compost to 0,5% on a dry mass basis. During a subsequent test 0,5% of ammonia-nitrogen was added to obtain nitrates by biological nitrification. Figure 8 shows that both ammonia- and nitrate-nitrogen additions had an adverse effect on the temperature curves, while chemical analyses indicated that none of the added ammonia-nitrogen was converted to nitrates during the test. It is possible that the

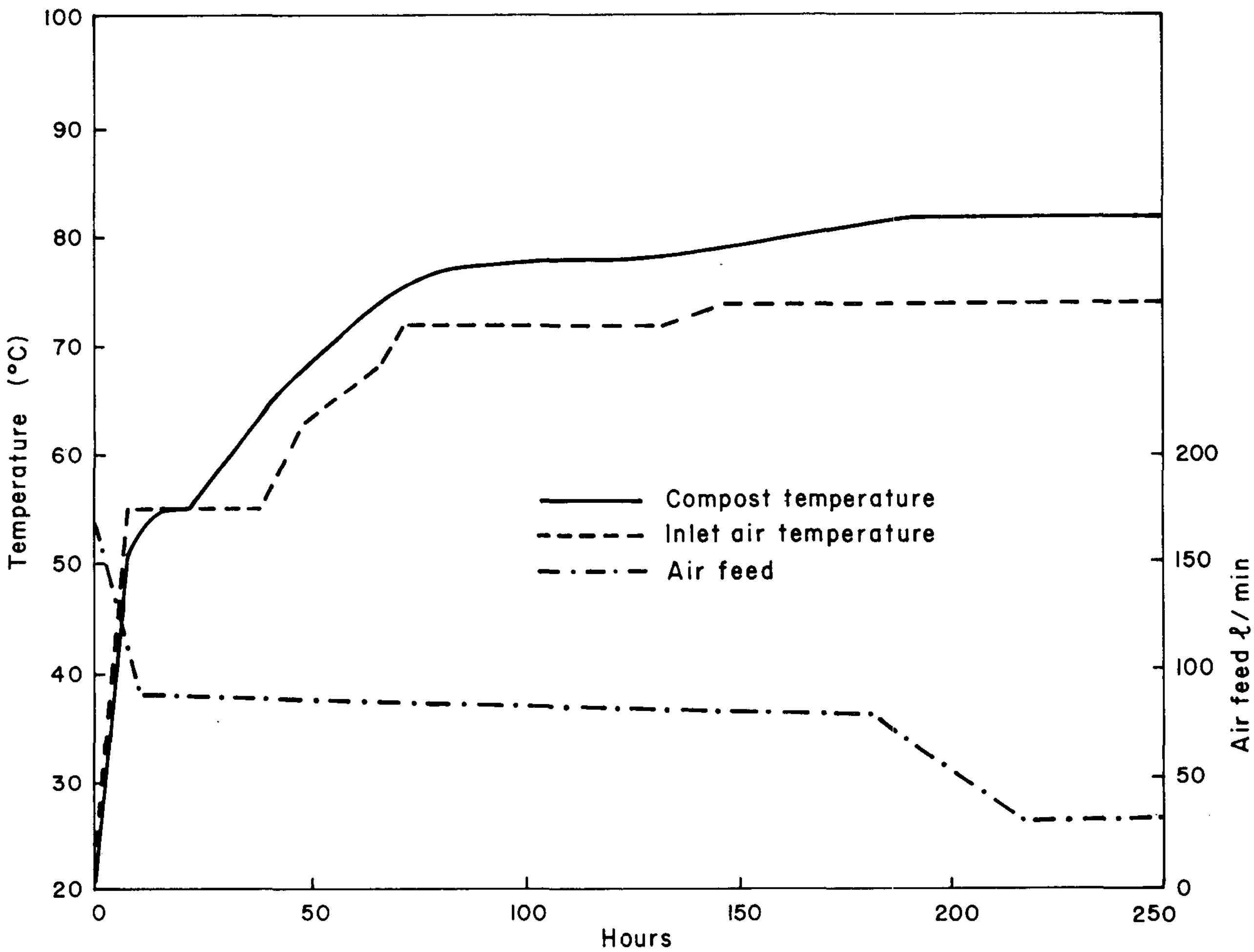

Figure 9
Temperature and air feed data for middle zone of pilot plant (Test 6)

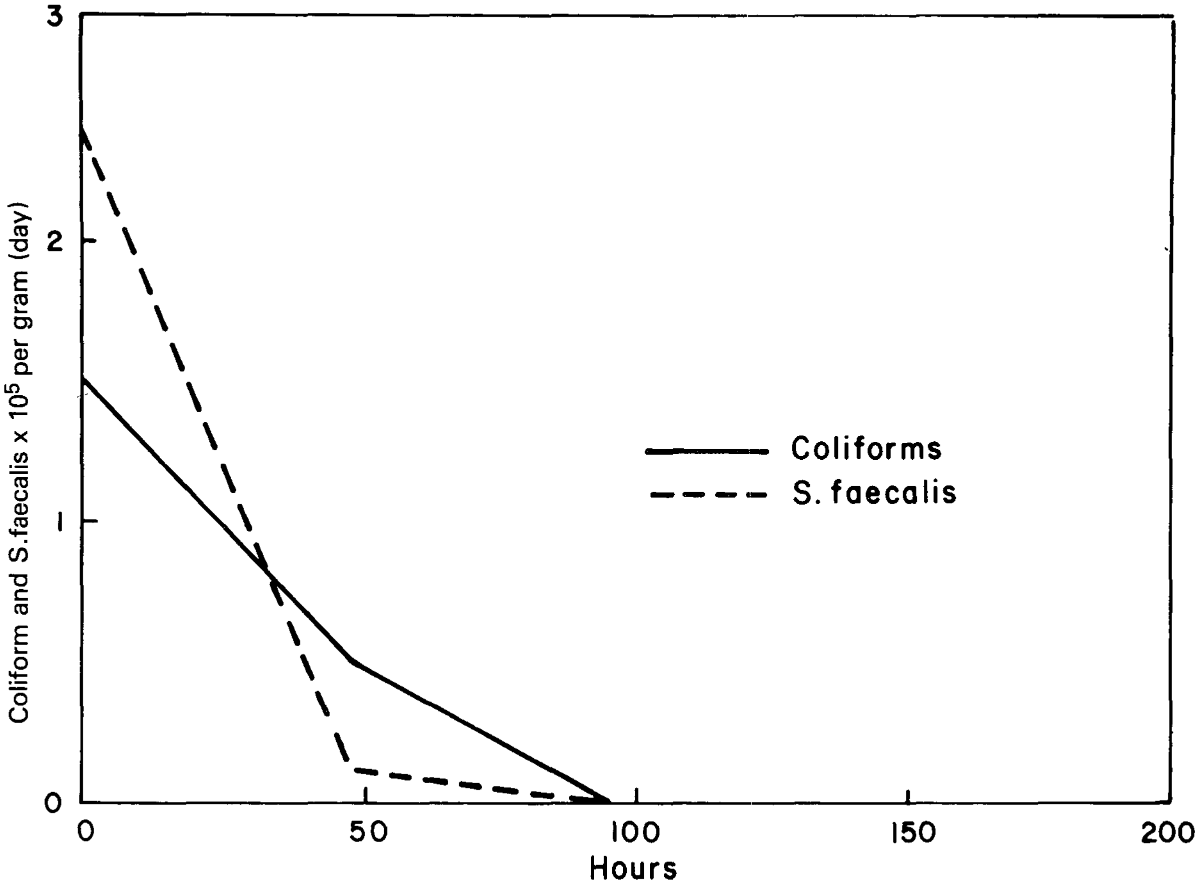

Figure 10
Elimination of coliforms and Streptoccoccis faecalis *in middle zone of pilot plant reactor (Test No 6)*

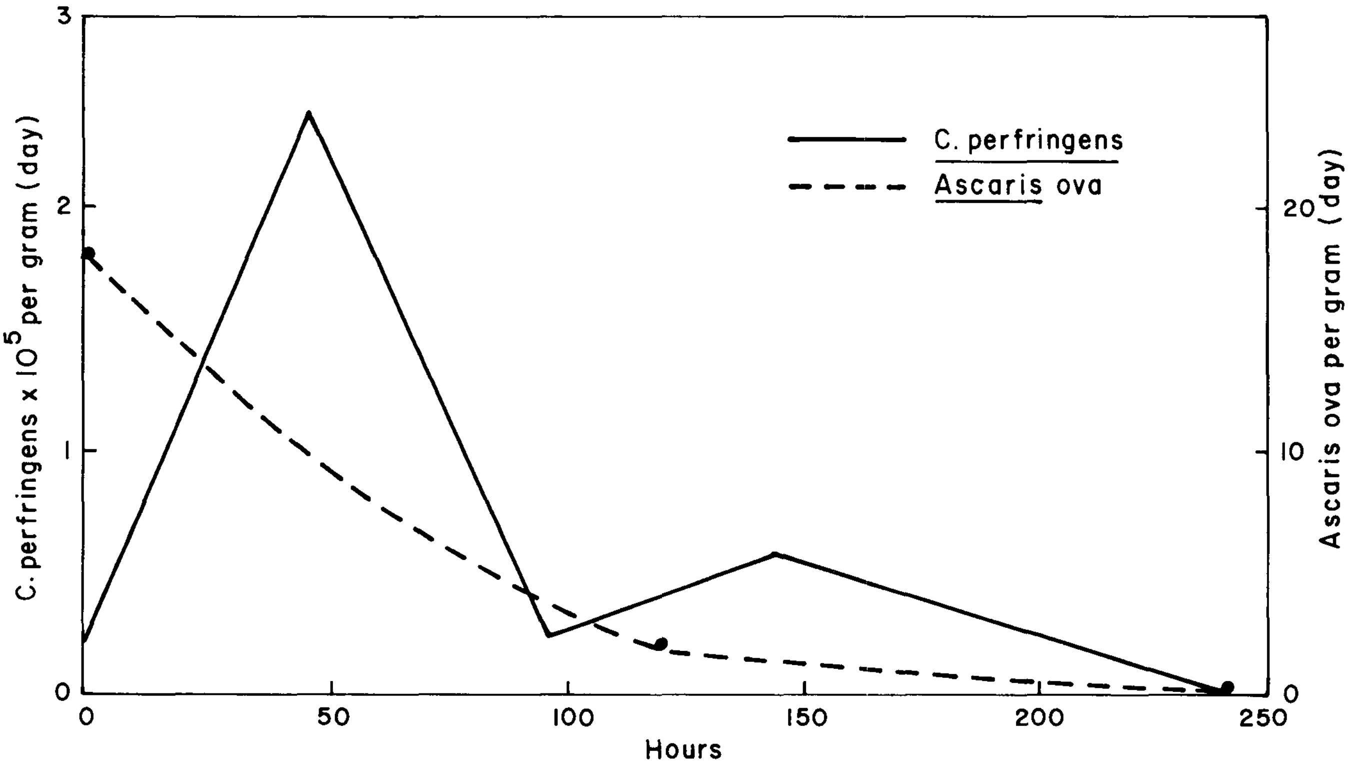

Figure 11
Elimination of Clostridium perfringens *and* Ascaris *ova in middle zone of pilot plant reactor (Test No 6)*

added quantity of nitrogen was too high, causing inhibition of microbiological growth. The necessity for nitrification during the initial stages has, therefore, not been confirmed and this aspect is being investigated further.

Test 6

Figure 9 gives data obtained in the middle zone of the reactor during a pilot plant run with mesophilic stage elimination. As expected, rates of temperature increase are lower than those obtained in the laboratory, which is probably the result of less efficient prevention of heat loss by means of insulation and inlet air heating and humidification. Nevertheless, temperatures in excess of 80°C were obtained after 160 h and could be maintained for at least 240 h. Oxygen requirements decreased considerably during the first 220 h as indicated by the air feed curve in Figure 9. The air feed was regulated to maintain a residual oxygen concentration of between 10 and 15%, since preliminary results of oxygen requirement studies showed that a residual carbon dioxide concentration of 5% had a beneficial effect on the rate of heat generation during the thermophilic stage.

In Figures 10 and 11 the mortality rates of Coliforms, *Streptococcus faecalis, Clostridium perfringens* and *Ascaris* ova in the middle of the reactor are illustrated. It can be seen that none of these organisms survived for longer than 240 h. Further bacteriological and helminthological studies are at present under way. Indications are that the pasteurization effect is less effective in the upper layers of the reactor owing to temperatures being lower by 20 to 30°C during the HLP and HAP. In practice these compost layers can be introduced into the bottom of the reactor for the next composting cycle.

Conclusions

Composting temperatures of higher than 80°C have been demonstrated in both laboratory and pilot plant studies. These temperatures can be attained by the activation of exothermic chemical reactions, by the prevention of heat losses from the composting mass, by regulating the residual oxygen and carbon dioxide concentrations and by eliminating the mesophilic stage of composting.

However, composting temperatures of 100°C have also been obtained in the laboratory. The chemical and physical mechanisms responsible for such high temperatures are probably similar to those that lead to spontaneous ignition in compost windrows and are being investigated at present.

Coliforms, *Streptococcus faecalis, Clostridium perfringens* and ova of *Ascaris lumbricoides* did not survive for more than 240 h in the middle zone of the reactor. This is a significant improvement over pasteurization during windrow composting where maturation periods of up to 70 days may be required to obtain the same effect.

Provided that raw sewage sludge is dewatered to about 60% moisture, HTC plants will utilize all the raw sludge produced by a community, thereby eliminating costly anaerobic sludge digestion at sewage treatment plants. The cost aspects of HTC are being studied.

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