APPLIED AND ENVIRONMENTAL MICROBIOLOGY, June 1981, p. 1321-1330 Vol. 41, No. 6
0099-2240/81/061321-10$02.00/0

Composting Process Control Based on Interaction Between Microbial Heat Output and Temperature†

S. T. MACGREGOR, F. C. MILLER, K. M. PSARIANOS, AND M. S. FINSTEIN*

Department of Environmental Science, Cook College, Rutgers University, New Brunswick, New Jersey 08903

Received 2 December 1980/Accepted 17 March 1981

Rational composting process control involves the interrelated factors of heat output, temperature, ventilation, and water removal. The heat is released microbially at the expense of organic material; temperature is an effect and, because it is a determinant of microbial activity, it is also a cause of heat output; ventilation supplies oxygen and removes heat, mainly through the vaporization of water; water removal results from heat removal. These relationships were implemented in a field-scale process of static-pile configuration, using a mixture of sewage sludge and wood chips. Heat removal was matched to heat output through a temperature feedback control system, thereby maintaining biologically favorable temperatures. The observations indicate that fundamentally there are two kinds of composting systems: those that are and those that are not temperature self-limiting. The self-limiting system reaches inhibitive temperatures (>60°C) which debilitate the microbial community, suppressing decomposition, heat output, and water removal. In contrast, non-self-limiting temperatures (<60°C) support a robust community, promoting decomposition, heat output, and water removal.

Composting is being widely adopted for the treatment of solid waste (8). This results from various regulatory pressures, particularly the ban on ocean dumping of sewage sludge scheduled to take effect at the end of 1981 (21).

In composting, a basic process control objective is to maximize microbial activity at the expense of the waste being treated. This is equivalent to maximizing metabolic heat output. To approach this objective, it is necessary to consider that, in the self-heating ecosystem, temperature is both effect and cause. The temperature is a function of the accumulation of heat generated metabolically, and simultaneously the temperature is a determinant of metabolic activity. The interaction between heat output and temperature is the centerpiece of rational control of the composting process.

The following summary of the heat output-temperature interaction is based on an earlier review (7) recently updated (5). 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 the 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 temperature most conducive to organic matter decomposition may be determined from reports in the literature based on specific, objective, measurements of activity (CO_2 output, heat output, etc.). Two suitable experimental designs have been followed. The first used the adiabatic apparatus to give free rein to the interplay between heat output and temperature (2, 3, 14, 18, 22). The second fixed the temperature in test chambers at selected levels (12, 17, 20, 23, 24). The results from both experimental approaches indicate that, in the thermophilic range, activity is greatest at 52 to 60°C and that a steep decline starts above this upper boundary.

Process stability, also, is favored by moderate rather than extreme thermophilic temperatures, judging from an investigation of bacterial species diversity at different composting temperatures (P. F. Strom, Ph.D. thesis, Rutgers University, New Brunswick, N. J., 1978; P. F. Strom and M. S. Finstein, Abstr. Annu. Meet. Am. Soc. Microbiol. 1979. Q89, p. 234). Diversity was slighter at 65 to 69°C and 60 to 65°C than at 55 to 61°C, 50 to 57°C, and 49 to 55°C.

Our present purpose was to devise a practical means of controlling temperature in field-scale composting and to evaluate such an approach to process control.

MATERIALS AND METHODS

Composting materials. Sludge was obtained from the Camden County Municipal Utilities Authority,

---

† Paper of the journal series, New Jersey Agricultural Experiment Station.

Jackson Street Sewage Treatment Plant, Camden, N.J. Approximately 90% of this material was primary sludge (not subjected to biological treatment). The remaining 10% consisted of "partially digested" sludge derived from a separate area.

Routine practice at the treatment plant is to add 1 kg of chloride-based polyelectrolyte polymer conditioning agent per metric ton of dry solids, followed by dewatering in a belt filter press. The resultant sludge cake has a moisture content of approximately 75% (wet weight), and the oven dry material has a volatile solids content of approximately 75%.

To provide porosity, sludge cake and virgin wood chips (nominally, 2.5 by 2.5 by 0.6 cm) were combined (approximately 1:1.8, wt/vol) and mixed in an industrial pug mill.

Composting pile. A pile consisted of a mixture of sludge and woodchips, with a base and cover of wood chips only. The pile contained approximately 6 (Fig. 1) or 18 (Fig. 2) metric tons of the sludge wood chip mixture.

Ventilation system. Corrugated plastic flexhose (4 inch [ca. 10 cm], ID) served as ventilation duct work. A section of perforated hose was buried in the wood chip base and was connected to a blower via a nonperforated section exterior to the pile. The small piles (Fig. 1), which are designated A, B, and C, were each ventilated by one 9-inch (ca. 23-cm) radial blade blower capable of delivering up to 530 ft^3 (ca. 15 m^3) of air per min. The large pile, designated T, was ventilated by four blowers, one at each end of the ducts (Fig. 2). The blowers were operated in the forced-pressure mode (F. C. Miller, S. T. MacGregor, K. M. Psarianos, J. Cirello, and M. S. Finstein, J. Water Pollut. Control Fed., in press).

Temperature control system. A temperature controller (Fenwal Inc., Ashland, Mass.; model 551) with an adjustable temperature set point continuously received and interpreted a signal from a thermistor in the pile (Fig. 3). When the signal indicated a temperature less than the set point, the controller actuated the blower on a periodic schedule preset with a timer. When the signal indicated a temperature greater than the set point, the controller directly actuated the blower, which remained in operation continuously until the temperature was lowered to less than the set point. Thus, the control system was based on the feedback of temperature information from a selected position in the pile.

Thermistor and thermocouple probes. The thermistor component of the control system, and thermocouples for monitoring the temperature, were mounted on wooden dowels (1⅝-inch [ca. 4-cm] diameter). The thermistor was housed in a steel pipe (⅜ inch [ca. 0.9 cm], ID) to dampen response and was fixed to the end of the dowel. A thermocouple made of 20-gauge copper-constantan wire was taped to the pipe housing, and additional thermocouples were taped to the dowel at 0.3-m intervals.

Gas sampling probe. These were fashioned from a length of steel pipe (¼ inch [0.6 cm], ID) closed at one end (19). A section of the pipe behind the closure was perforated to allow gas entry.

Monitoring, automatic. The thermocouples led to a recording monitor (Doric Scientific Corp., Cedar Grove, N.J.; Digitrend 2000) which logged the data. The gas sampling probe led via Tygon tubing to a 2-liter condensate trap packed with glass wool and then to a four-point multiplexing system (5). The multiplexer sequentially interrogated three pneumatic inputs, each representing one probe, using a pump of nominal 1-l/min flow. A fourth input was for ambient purge between samples. Sample cycles were 30 min long and were initiated every 4 h.

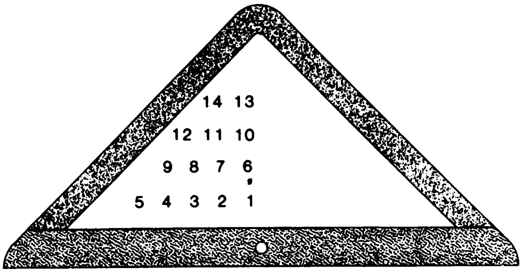

FIG. 1. *Six-metric-ton composting pile, cross-sectional representation (not to scale). Stippled area, wood chip base (length, 4.5 m; width, 4.5 m; height, 0.3 m) and cover (thickness, 0.2 m); clear area, mixed sludge and wood chips (height, 2.1 m); open circle in base, perforated flexhose duct (length, 2.8 m); positions 2 through 13, thermocouples; position 1, thermocouple and thermistor; position g, inlet port of gas sampling probe.*

Gas samples collected by the multiplexer were passed through an infrared CO_2 analyzer (Beckman Instruments, Inc., Los Angeles, Calif.; model 315).

Blower operation was monitored by an event recorder (Rustrack, East Greenwich, R.I.; no. 292-4).

Monitoring, manual. Oxygen was determined with a portable analyzer (Bacharach Instrument Co., Pittsburgh, Pa.; model 524).

Samples of composting material were obtained with a clamshell-type posthole digger. The locations sampled corresponded approximately to position 6 in the small piles (Fig. 1) but were at various points along the length of the pile. The corresponding site for the large pile (Fig. 2) was position 24. Sample material (minus the wood chips) was dried at 104°C, and the moisture content was expressed on a wet weight basis. To determine pH, sample material was made into a slurry with distilled water.

An odor test was performed in the laboratory with the samples obtained on one occasion. The material was placed into screw-cap jars of 1-pt (ca. 0.5-liter) capacity, such that the jars were one-third full. Randomly selected individuals (excluding project personnel) were asked to evaluate the samples on a scale of −5 to +5 (−5 = most unpleasant; 0 = neutral; +5 = most pleasant). The first test was started approximately 4 h after sampling. At termination, the jars were capped and the material was stored at room temperature for retest on the following day. On the 1st test day, the panel consisted of 11 males and 6 females; and on the 2nd day, it consisted of 17 males and 12 females. Six of the individuals participated on both days.

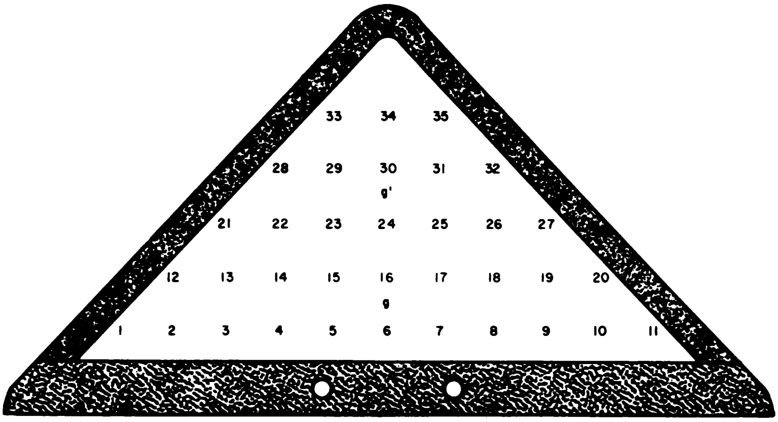

FIG. 2. *Eighteen-metric-ton composting pile, cross-sectional representation (not to scale). Stippled area, wood chip base (length, 11 m; width, 4.3 m; height, 3.0 m) and cover (thickness, 0.15 m); clear area, mixed sludge and wood chips (height, 1.8 m); open circles in base, perforated flexhose duct (length, 8.3 m); positions 1 through 5 and 7 through 35, thermocouples; position 6, thermocouple and thermistor; positions g and g', inlet ports of gas sampling probes.*

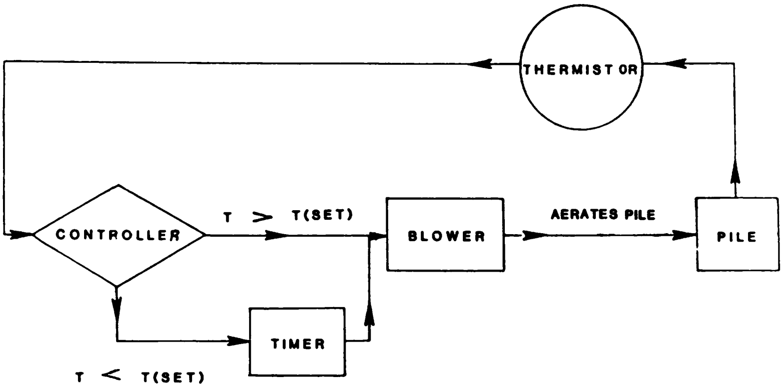

FIG. 3. *Schematic of the temperature feedback-blower control system. The thermistor was at position 1 in the 6-metric-ton piles (Fig. 1) and at position 6 in the 18-metric-ton pile (Fig. 2).*

RESULTS

Relationship between CO_2 and O_2. The data collection system was automatic for CO_2, but manual for O_2. To more fully utilize the automatically collected data, the relationship between CO_2 and O_2 was examined as part of preliminary runs. Three sets of gas samples representing various pile locations were obtained, two sets (23 and 17 samples) from a single pile on separate occasions and a third set (23 samples) from a different pile. The sites of gas withdrawal were along a grid transect at 0.3-m intervals. Each sample was assayed for the two gases. The overall mean of the sums (CO_2 plus O_2) was 20.78 ($\sigma = 1.01$). Analysis of variance indicated that the three sets of sums were not significantly different ($P < 0.5$). Thus, within the range of CO_2 levels encountered in this study (0.1 to 6.5%), the O_2 content could be estimated through the relationship $\%O_2 = 20.78 - \%CO_2$.

Performance at selected temperature set points. Three piles, each consisting of 6 metric tons of the sludge wood chip mixture, were made on 10 May 1979, and the main part of the experiment was terminated on 31 May. The set points assigned to the temperature controllers were: pile A, 45°C; pile B, 55°C; pile C, 65°C. During the experimental period, a weather station 6 km southeast of the composting site reported air temperatures of 8.9 to 30.6°C (mean, 18.5°C) and rainfall of 13 cm in 12 occurrences (13).

(i) Blower operation. In pile A, blower operation first exceeded that scheduled by timer at h 12, indicating that the controller had responded to a thermistor temperature of >45°C

(Fig. 4). This marks the start of the period of temperature feedback control. Blower operation was nearly continuous from h 80 to 150. Feedback control terminated at h 352, and blower operation reverted to that scheduled by timer (7% of the time).

For pile B, the period of feedback control was from h 26 to 214, during which blower operation peaked at 45% at h 70. For pile C, the period of feedback control was h 28 to 84, and the peak was 12% at h 50.

(ii) Pile temperature. Figure 5 shows representative temperatures. In all of the piles, the thermistor and a thermocouple were both at position 1. Table 1 summarizes the temperature data from the period of feedback control. During this period, the median temperature in pile A exceeded the controller setting for this pile by 3°C, whereas the excess values for piles B and C were 7 and 2°C, respectively.

In pile A, the temperature at position 1 during the period at feedback control was essentially that of the assigned set point (45°C). The only appreciable departure from the set point occurred between h 92 to 136. During this period, the peak temperature was 53°C, at h 112. The departure occurred while blower operation was continuous.

Control was generally less precise at the lateral positions (e.g., A3 and A12). In this direction, the least precise control was at the outermost position. Higher temperatures occurred in the uppermost areas of the pile (e.g., compare the temperatures at positions A1, A6, and A13).

Similarly, in piles B and C during the period of feedback control, there was a close corre-

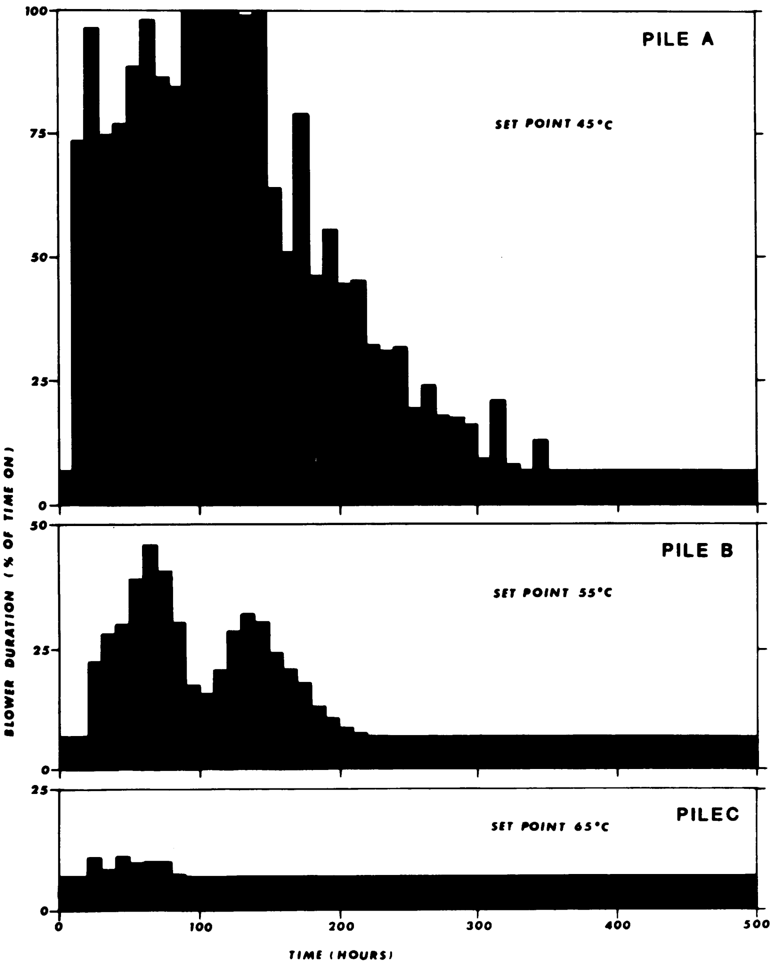

FIG. 4. *Mean blower operation per 10 h.*

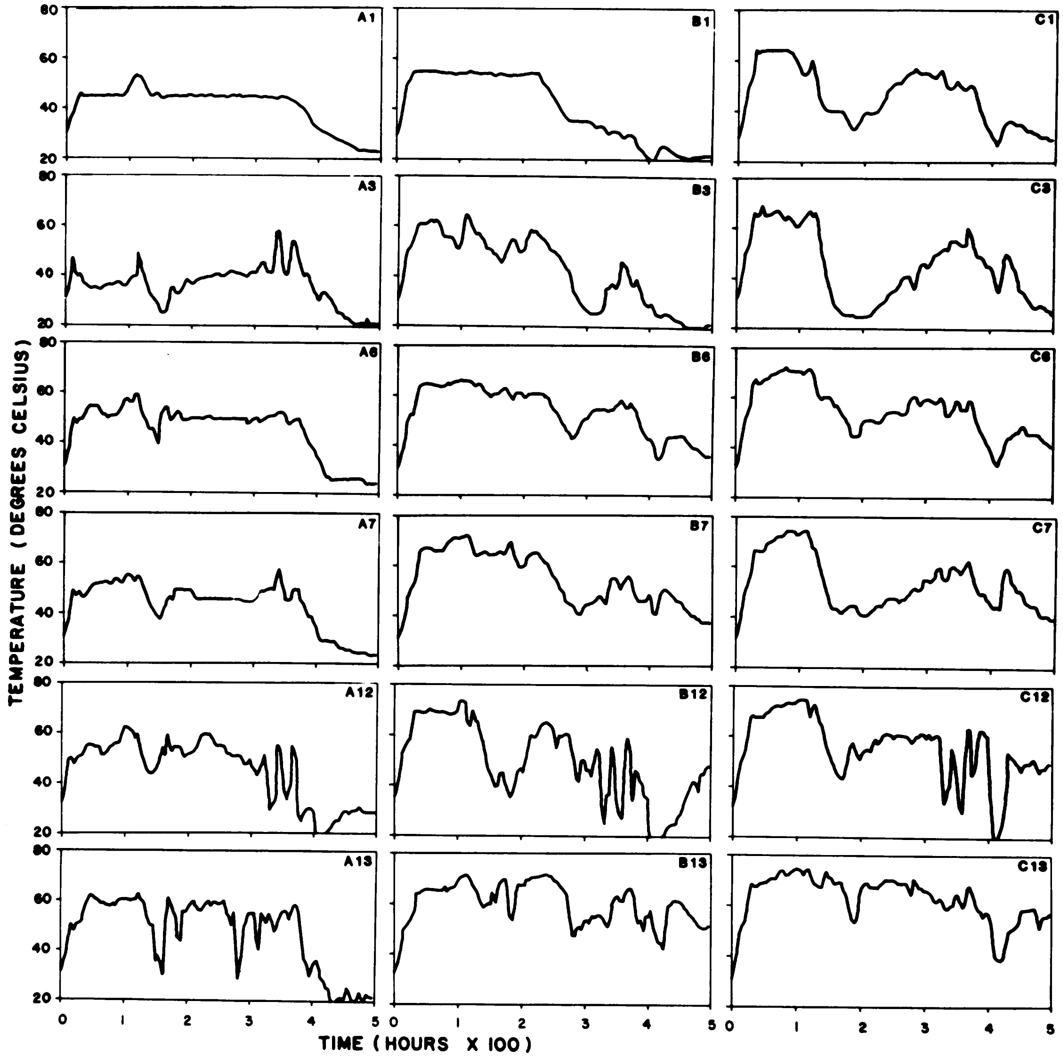

FIG. 5. *Temperatures at selected positions. Letter is pile designation; number is position in pile (see Fig. 1).*

spondence between the set points (55° and 65°C, respectively) and pile temperatures near the thermistors (positions B1 and C1). Lateral to these positions, and in the upward direction, control was less precise. In pile C, the ventilation scheduled by timer generally induced early, precipitous temperature declines.

(iii) Carbon dioxide. Where the record is complete (piles A and C), the highest CO_2 levels occurred before the initiation of temperature feedback control (Fig. 6). During the period of feedback control, the CO_2 values averaged approximately 2, 3, and 4% for piles A, B, and C, respectively. During the terminal period of timer-scheduled blower operation, the CO_2 values were lower.

(iv) pH. The starting pH was 6.3, and this increased, at a different rate in each pile, to approximately 8.2 (Fig. 7). This was followed by a slight decline. A secondary increase in pile A started after h 380.

(v) Moisture content. In pile A, the starting moisture content of 76% decreased to 22% in 15 days (Fig. 7). In piles B and C, the decrease was to 40% in 18 days.

(vi) Odor. The material obtained on day 4 was evaluated by odor test panels. The first test started approximately 4 h after sampling, and the second test (after storage at room temperature) started the next day. The mean scores for the 1st day were: pile A, −1.35; pile B, −2.00; pile C, −3.00. For the 2nd day, these were: pile

TABLE 1. *Temperature during the periods of temperature feedback control*

Controller set point (°C)	Period of feedback control (h)	Pile temp (°C)		Observations[a]	
		Range	Median	No.	% > 60°C
45 (pile A)	12-352	25-63	48	1,020	1.8
55 (pile B)	26-214	18-78	62	641	58
65 (pile C)	28-84	64-74	67	182	100

[a] 60°C is considered the threshold to significant self-limitation (see text).

A, −2.33; pile B, −3.30; pile C, −3.85. The more negative the value, the more unpleasant the odor.

(vii) Rewet. Each pile was rewet with tap water on three occasions, between h 500 and 970. Each water addition provoked a temperature ascent, which subsided before the subsequent water addition. The responses tended to get weaker with time.

Performance with temperature feedback control and with continuous ventilation. An 18-metric-ton pile (designated pile T) was made on 3 August 1979, and the run was terminated on 15 August. The thermistor was centrally sited, at position 6 (Fig. 2). The temperature controller was set at 45°C with the intention of mimicking the operation of pile A. During the experimental period, ambient air temperatures ranged from 13.3 to 33.9°C (mean, 25.3°C), and rainfall amounted to 8.2 cm in six occurrences (13).

(i) Period of temperature feedback control. The control system equipment functioned normally from time zero to h 130 (Fig. 8). Temperature feedback control was initiated at h 14, and continuous operation of the blower started at h 54. The temperature was under control until h 60, having stabilized at approximately 45°C near the thermistor (position T6), 35°C directly over the ducts (e.g., position T5) and 60°C at higher pile levels (e.g., position T30). Subsequently, during a period of continuous blower operation, the temperature at position T6 departed from the set point value to a peak of 64°C at h 90. More precise control of temperature was regained at h 120. Although of greater magnitude, this temporary loss of temperature control in pile T was similar to that experienced in pile A between h 92 and 132.

From time zero to h 130, the CO_2 content in the lower part of the pile (Fig. 9a) was generally from 0.5 to 2%. At the higher gas sampling site (Fig. 9b), CO_2 reached 9.5% before the period of feedback control whereupon, until h 130, it ranged from 1 to 4%. During this period, the starting pH of 5.3 increased to 7.3, and the starting moisture content of 70% decreased to 44%.

(ii) Period of continuous ventilation. Pile T's control system failed at h 130, manifested in the nonresponse of the blowers to pile temperatures higher than the set point value (Fig. 8). The loss of blower operation induced a sharp upturn in temperature. On h 150, the blowers were manually turned on for continuous operation. This induced a sharp downturn in pile temperature.

The loss of blower operation induced a sharp upturn in CO_2 levels, which was reversed by the manual intervention (Fig. 9). Thereafter, CO_2 was at the lower limit of detectability (<0.1%). During this period of continuous ventilation, the pH tended to increase. The moisture content decreased from 43 to 40%. The latter observation may be compared with the decrease in pile A, from 48 to 23%, during the comparable time period, during which, however, ventilation was governed by the temperature feedback control system.

DISCUSSION

A practical means of controlling temperature was devised in the form of the temperature feedback control system in conjunction with forced-pressure ventilation. The implications of this approach to process control are discussed here.

A definitive comparison of pile A (coolest), pile B (intermediate), and pile C (hottest) based on CO_2 output and heat output in this open system is not possible, as these measurements of decomposition cannot be reliably quantified from the data. The results of the odor test indicate that the rate of decomposition was A > B > C. The moisture content data provide a similar indication, as is developed through a consideration of heat removal from the composting piles.

The important mechanisms of heat removal are vaporization and dry air convection, both of which are dependent on ventilation. Other mechanisms associated with heat exchange at surfaces (radiation, conduction) are negligible in this large, well-insulated system (5). The ventilation-dependent mechanisms are ranked in the following hypothetical exercise.

Air enters the pile at 25°C and 60% relative humidity. The mass of water vapor/mass of dry air (ω) is 0.012, and the heat content or enthalpy

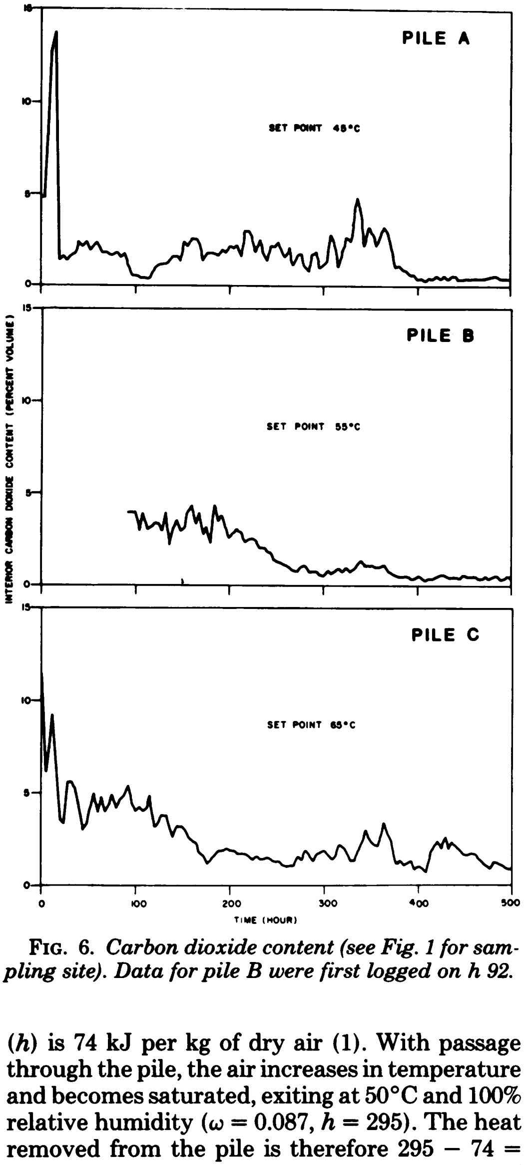

FIG. 6. *Carbon dioxide content (see Fig. 1 for sampling site). Data for pile B were first logged on h 92.*

(*h*) is 74 kJ per kg of dry air (1). With passage through the pile, the air increases in temperature and becomes saturated, exiting at 50°C and 100% relative humidity ($\omega = 0.087$, $h = 295$). The heat removed from the pile is therefore $295 - 74 = 221$ 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 $25/221 = 11\%$ of the total removal. The remaining 89% of the heat is removed through vaporization. Changing the exit air temperature to 70°C gives $\omega = 0.278$ and $h = 824$. Heat removal now amounts to 750 kJ per kg of dry air, 94% of it through vaporization. Thus, in the temperature range of interest, approximately $^9\!/_{10}$ of the heat is removed through vaporization.

Consequently, the decrease in moisture content during composting indicates organic matter decomposition. This is because drying and decomposition are linked via heat output and vaporization. The observation that pile A dried faster than piles B and C therefore represents a field-scale demonstration of the heat output-temperature interaction concept, which requires the most extensive microbial heat output to occur in the coolest pile.

Faster and more complete drying at relatively moderate composting temperatures occurred in later runs also (F. C. Miller, S. T. MacGregor, K. M. Psarianos, and M. S. Finstein, unpublished data), summarized as follows. When process control mimicked pile A, the overall moisture content decrements were: 6-metric-ton pile, 75% → 30% in 15 days; 27-metric-ton pile, 75% → 20% in 8 days; 36-metric-ton pile, 74% → 29% in 13 days. When process control was according to the Beltsville method (26), providing temperatures higher than that of pile C, the decrement was: 36-metric-ton pile, 74% → 68% during the standard 21-day processing period. Extreme thermophilic temperatures and slight drying are characteristic of this method (15, 25, 26).

In pile A, the period of temperature feedback control ceased at h 352, at which time the moisture content was approximately 25%. Rewetting induced mild reheating, suggesting that avail-

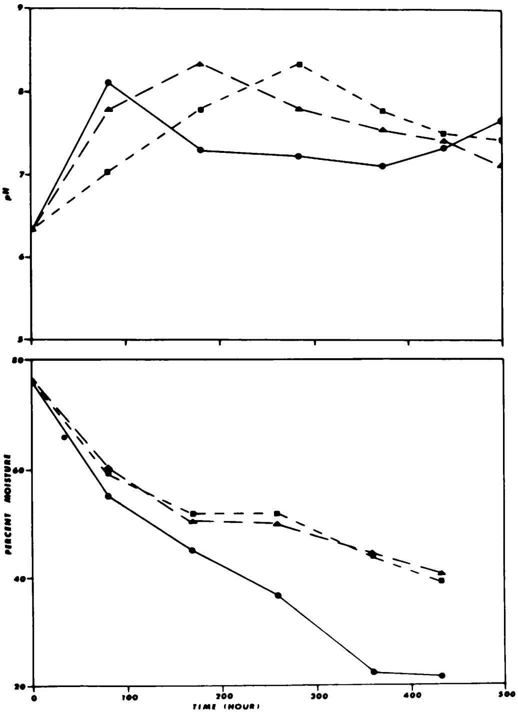

FIG. 7. *pH and moisture content in the three piles. Symbols: ●, pile A; ▲, pile B; ■, pile C.*

able substrate was partially depleted whereas available water was exhausted. In pile C, the period of feedback control ceased at h 84, at which time the moisture content was approximately 60%. This cessation is attributed to the debilitating effect of high temperature on the microbial community and its capacity to generate heat. Consistent with this view, the set point temperature (65°C) was not sustained against the minimal ventilation scheduled by timer (blower operation for 7% of the time).

Although strong ventilation demanded by extensive heat output effected fast drying, strong ventilation unrelated to heat output did not have this effect. Consider, for example, pile T before and after the control system malfunction. Beforehand, a period of continuous blower operation by demand was accompanied by fast drying. The malfunction with its loss of blower response caused a sudden temperature upturn, presumably debilitating the microbial community and its capacity for heat output. When continuous blower operation was resumed, by imposition, the pile cooled abruptly and little further drying occurred.

This behavior of pile T is considered in a second hypothetical exercise. It is assumed that an isenthalpic condition (no change in heat content with passage of air through the pile) prevailed during the period of imposed continuous ventilation, which would be true in the absence of heat output. Inlet conditions are again taken to be 25°C and 60% relative humidity. The air becomes saturated (100% relative humidity) with passage through the pile. Since h is unchanged (74 kJ per kg of dry air), vaporization cools the air, and the exit temperature is 19.5°C (ω = 0.014). Water removal thus amounts to 0.014 − 0.012 = 0.002 kg of water vapor per kg of dry air, which is slight compared with that removed when the exit air is 50°C (= 0.075 kg of water vapor per kg of dry air). The behavior of pile T during the latter part of the run was consistent with a near-isenthalpic condition. Thus, any attempts to dry sludge through ventilation without benefit of heat output would be unrewarding. Water removal, as well as organic matter decomposition, is a major waste treatment objective (9).

We now consider process control from the vantage point of ventilation. Ventilation provides O_2 for aerobic respiration and removes heat (and hence water). Although the temperature feedback control system responds directly to temperature, indirectly the response is to microbial heat output and oxygen consumption.

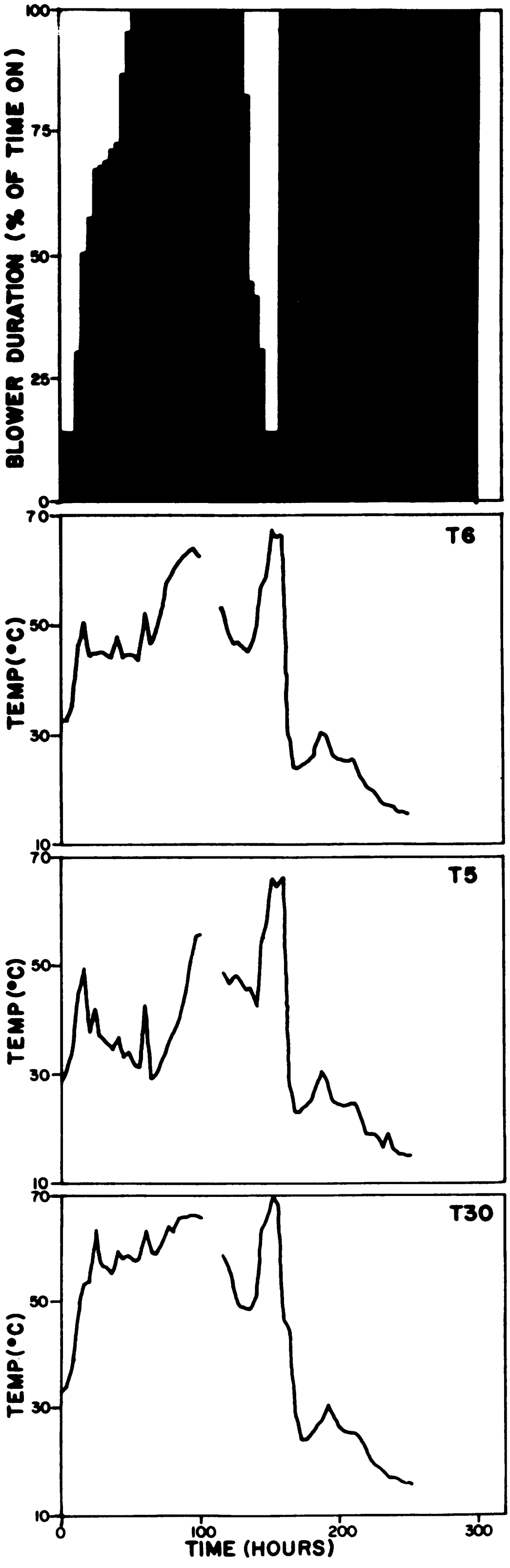

FIG. 8. *Pile T mean blower demand per 4 h and temperature at selected sites (see Fig. 2).*

This is because the temperature is a function of heat output, which in turn is a function of aerobic respiration. The feedback approach to control thus assures a well-oxygenated condition, as blower demand and oxygen demand are indirectly linked.

The instantaneous level of oxygen reflects the balance between two opposing tendencies: the uptake of oxygen microbially and its replenishment through ventilation. Thus, high rates of both uptake and replenishment (e.g., pile A), or low rates of both of these factors (e.g., pile C), can result in similar oxygen levels (compare Fig. 4 and 6). Contrary to what seems to have been suggested (26), the level of oxygen per se does not indicate process status.

To evaluate process status, several interacting factors must be considered (Table 2). These principles pertain to composting processes in general, whether the mass is static or agitated, whether or not a reactor structure is used, and whether the operation is batch or continuous. In static-pile configuration, the temperature self-limiting system is represented by the Beltsville

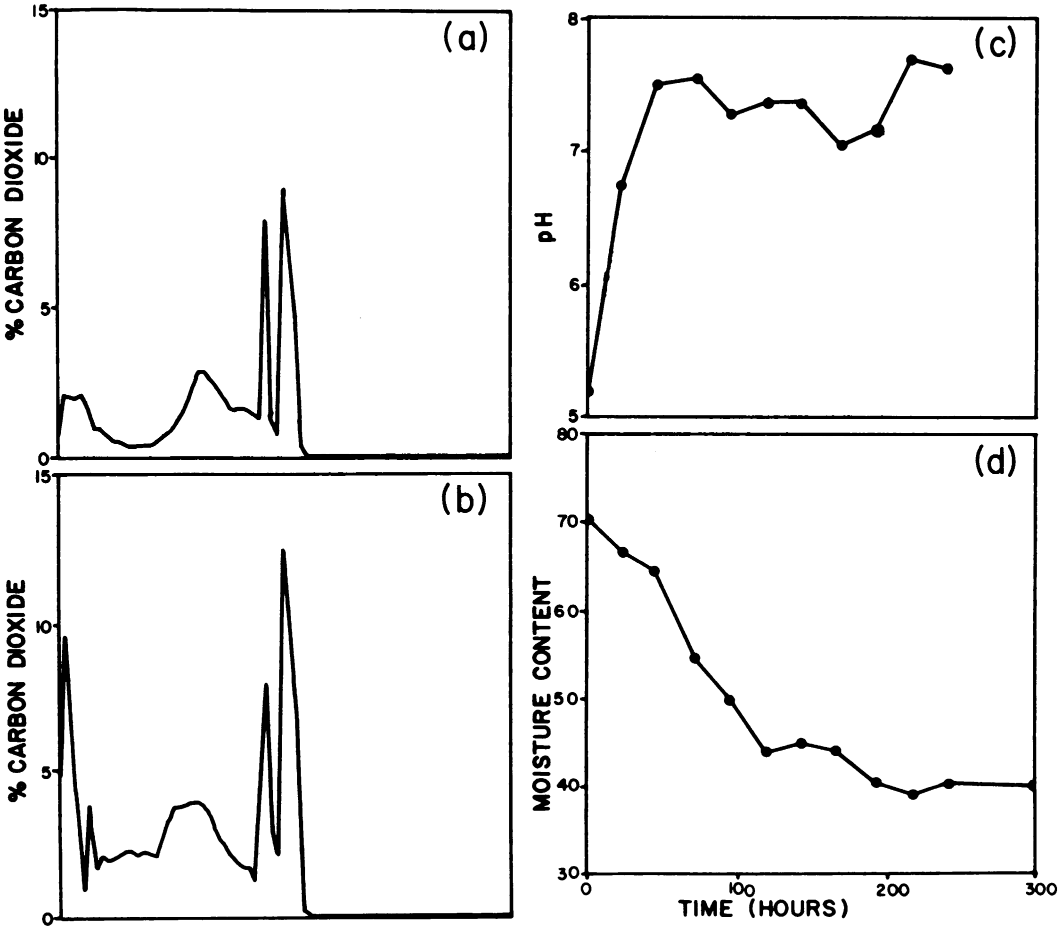

FIG. 9. *Pile T carbon dioxide content: (a) site g; (b) site g′ (see Fig. 2). Other data are of pH (c) and moisture content (d).*

TABLE 2. *Fundamentally different composting systems*

System	Temp (°C)	Microbial community	O_2 uptake and heat output	Ventilation requirement to maintain an oxygenated condition	Vaporization and drying
Temperature self-limiting	70	Debilitated	Slight	Slight	Slight
Temperature non-self-limiting	55	Robust	Great	Great	Great

process (4, 16, 25, 26), and the temperature non-self-limiting system is represented by pile A, in part by pile T, and by the scale-up runs noted briefly above. The implementation of the temperature non-self-limiting principle in static-pile configuration is named the Rutgers process.

Finally, an earlier analysis (9) of the physical factors which effect the composting process was stimulating; however, neglect of the critical biological factors limited its applicability (6). This was only partially corrected in a later treatise (11). We agree that the need to integrate physical and biological factors may be equated to the need to integrate thermodynamic and kinetic considerations (10). Nonetheless, in the special case of the composting process, thermodynamic behavior is a direct consequence of the heat output-temperature interaction, and this interaction must serve as the focal point of the analysis.

ACKNOWLEDGMENTS

The work was supported by funds from the U.S. Environmental Protection Agency Region II (grant C340678010), New Jersey Department of Environmental Protection, Camden County Municipal Utilities Authority; U.S. Environmental Protection Agency, Municipal and Environmental Research Laboratory, Ultimate Disposal Section (grant R806829010); the New Jersey Agricultural Experiment Station.

LITERATURE CITED

1. **American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.** 1963. Psychometric charts nos. 1 and 3. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.,
2. **Carlyle, R. E., and A. G. Norman.** 1941. Microbial thermogenesis in the decomposition of plant material. II. Factors involved. J. Bacteriol. **41**:699–724.
3. **Dye, M. H., and H. P. Rothbaum.** 1964. Self-heating of damp wool. Part 2. Self-heating of damp wool under adiabatic conditions. N.Z. J. Sci. **7**:97–118.
4. **Epstein, E., G. B. Willson, W. D. Burge, D. C. Mullen, and N. K. Enkiri.** 1976. A forced aeration system for composting wastewater sludge. J. Water Pollut. Control Fed. **48**:688–694.
5. **Finstein, M. S., J. Cirello, S. T. MacGregor, F. C. Miller, and K. M. Psarianos.** 1980. Rational approach to composting process control. Final report to USEPA, NJDEP, CCMUA. Rutgers University, New Brunswick, N.J.
6. **Finstein, M. S., J. Cirello, S. T. MacGregor, F. C. Miller, D. J. Suler, and P. F. Strom.** 1980. Discussion of paper by R. T. Haug. J. Water Pollut. Control Fed. **52**:2037–2042.
7. **Finstein, M. S., and M. L. Morris.** 1975. Microbiology of municipal solid waste composting. Adv. Appl. Microbiol. **19**:113–151.
8. **Goldstein, J.** 1980. An overview of composting installations. Compost Sci. **21**(4):28–32.
9. **Haug, R. T.** 1979. Engineering principles of sludge composting. J. Water Pollut. Control Fed. **51**:2189–2206.
10. **Haug, R. T.** 1980. Author's response. J. Water Pollut. Control Fed. **52**:2042–2044.
11. **Haug, R. T.** 1980. Compost engineering: principles and practice. Ann Arbor Science, Ann Arbor, Mich.
12. **Jeris, J. S., and R. W. Regan.** 1973. Controlling environmental parameters for optimum composting (part I). Compost Sci. **14**(1):10–15.
13. **National Oceanic and Atmospheric Administration.** 1979. Climatological data, New Jersey, vol. 83. National Climatic Center, Asheville, N.C.
14. **Niese, G.** 1959. Mikrobiologische Untersuchungen zur Frage der Selbsterhitzung organischer Stoffe. Arch. Mikrobiol. **34**:285–318.
15. **Olver, W. M. Jr.** Undated. Static pile composting of municipal sewage sludge: the process as conducted at Bangor, Maine. U.S. Environmental Protection Agency, Washington, D.C.
16. **Parr, J. F., E. Epstein, and G. B. Willson.** 1978. Composting sewage sludge for land application. Agric. Environ. **4**:123–137.
17. **Rothbaum, H. P.** 1961. Heat output of thermophiles occurring on wool. J. Bacteriol. **81**:165–171.
18. **Rothbaum, H. P.** 1963. Spontaneous combustion of hay. J. Appl. Chem. **13**:291–302.
19. **Strom, P. F., M. L. Morris, and M. S. Finstein.** 1980. Leaf composting through appropriate, low level, technology. Compost Sci. **21**(6):44–48.
20. **Suler, D. J., and M. S. Finstein.** 1977. Effect of temperature, aeration, and moisture on CO_2 formation in bench-scale, continuously thermophilic composting of solid waste. Appl. Environ. Microbiol. **33**:345–350.
21. **United States Code.** 1976. Marine protection, research, and sanctuaries act of 1972, as amended. (Public Law 92-532, as amended.) **33**:1401–1444.
22. **Walker, I. K., and W. J. Harrison.** 1960. The self-heating of wet wool. N.Z. J. Agric. Res. **3**:861–895.
23. **Wiley, J. S.** 1956. I. Progress report on high-rate composting studies. Proc. Ind. Waste Conf. **11**:334–341.
24. **Wiley, J. S.** 1957. II. Progress report on high-rate composting studies. Proc. Ind. Waste Conf. **12**:596–603.
25. **Willson, G. B., J. F. Parr, and D. C. Casey.** 1978. Criteria for effective composting of sewage sludge in aerated piles and for maximum efficiency of site utilization, p. 79–87. *In* Proceedings of the National Conference on Design of Municipal Sludge Composting Facilities. Information Transfer, Inc., Rockville, Md.
26. **Willson, G. B., J. F. Parr, E. Epstein, P. B. Marsh, R. L. Chaney, D. Colacicco, W. D. Burge, L. J. Sikora, C. F. Teste, and S. Hornick.** 1980. Manual for composting sewage sludge by the Beltsville aerated-pile method. Report EPA-600/8-80-022 Municipal Environmental Research Laboratory, Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.