composting dewatered sewage sludge

COVER: *Some aerobic, therophilic microorganisms associated with the composting process: Streptomyces colonies, Pseudomonas flourescens, Aspergillus fumigatus.*

composting dewatered sewage sludge

This report (SW–12c) was written for the Bureau of Solid Waste Management
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The Eimco Corporation
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foreword

Sometimes it is said that solid wastes are all those wastes that don't go up the chimney or down the sewer. One exception to this rule-of-thumb definition is that the waterborne wastes in sewers eventually are treated to effect removal of the solids. Thus, the final disposal of sewage sludge becomes a concern in solid waste management.

Among the methods used for disposing of sewage sludge are: anaerobic digestion, incineration, burial, and application to farmland. All of these methods depend upon the concentration of the sewage sludge solids for the best operation, and, except for anaerobic digestion, this usually includes dewatering the sludge. Except for incineration, these dewatering systems produce a sludge that still contains 70 percent moisture. Further dewatering of the sludge to reduce its volume and weight is desirable to facilitate its disposal. This study demonstrates the technical feasibility of composting to effectively treat dewatered sewage sludge alone to produce a stable hygienic material. The final compost had a quality similar to soil conditioner, the nitrogen–phosphorus–potassium ratio was the same as in cattle manure, and the material was found to be free of viable plant seeds and pathogens. Thus, the field of solid waste management is presented with another engineering alternative, which includes the possibility of a final disposal for sewage sludge with a concomitant transformation of waste solids into useful solids.

—Richard D. Vaughan, *Director*
Bureau of Solid Waste Management.

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abstract

Stabilization and final disposal of sewage sludge is of primary concern in waste treatment. The purpose of this study was to determine the feasibility of composting dewatered sewage sludge, to establish basic design criteria, and to determine the quality of the final compost.

The pilot-plant study was made with the use of a 40-cu-ft mechanical composter designed by The Eimco Corporation. Provisions were made to mix and aerate the compost at all times. A pilot, vacuum, continuous belt-type filter was used to dewater sewage sludge before it was fed into the composter.

The following general conclusions were established based on results of the pilot-plant operation.

1. Composting of dewatered sewage sludge is technically feasible. The data indicated volume and weight reductions of 60 to 85 percent.
2. Mixing and aerating on a continuous basis were required to ensure a high rate of treatment and to maintain aerobic conditions.
3. Recycling the compost was beneficial in adjusting moisture and in seeding the filter cake feed to the composter.
4. The final compost had a fertilizer value (nitrogen-phosphorus-potassium) about the same as cattle manure and was found free of viable plant seeds and indicator pathogens.
5. Chemicals used for conditioning of sewage sludge before dewatering affected process capacity and final product characteristics.

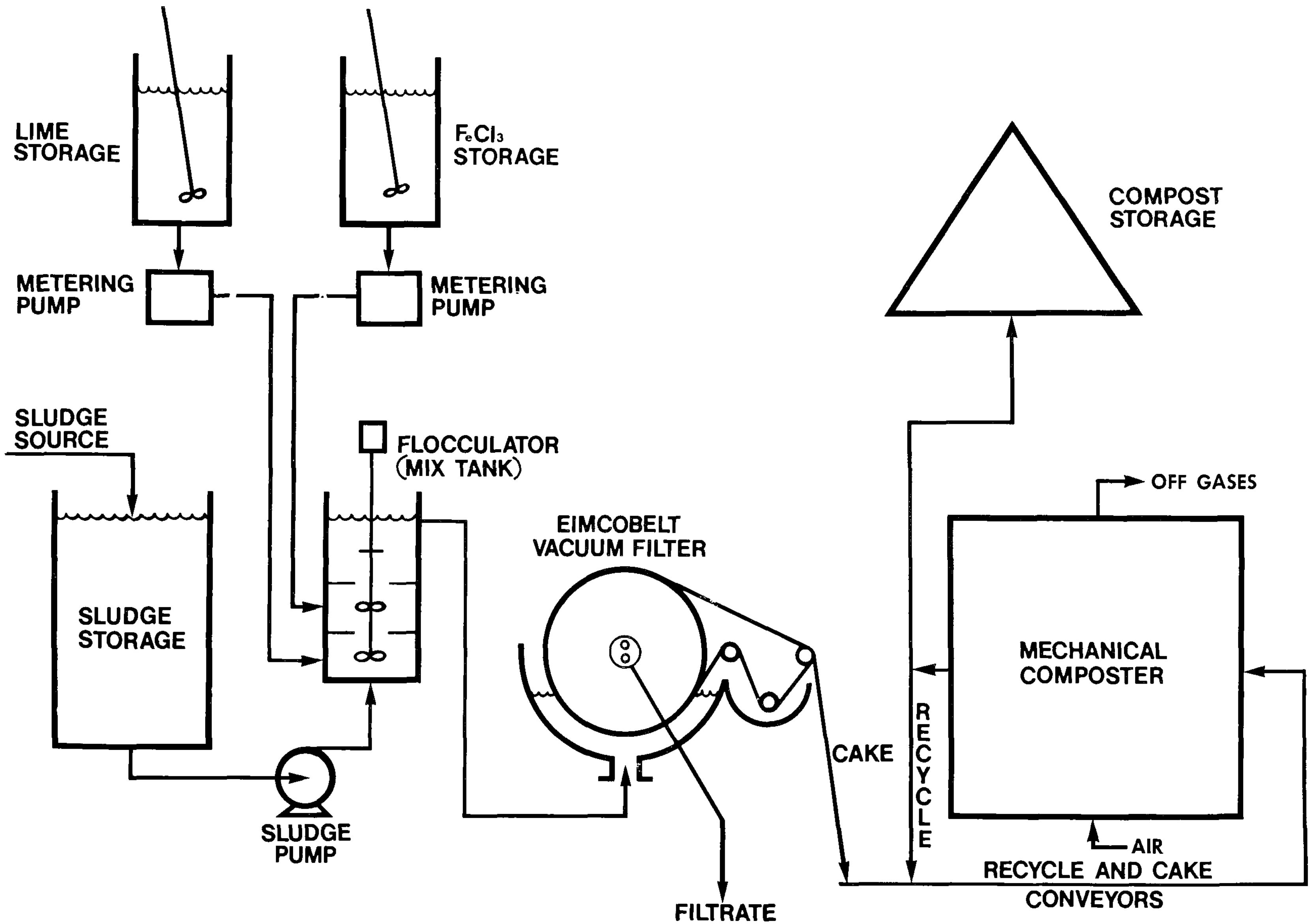

FIGURE 1. The process for composting of dewatered sewage sludge.

composting dewatered sewage sludge

TREATMENT AND FINAL DISPOSAL of sewage sludge represent a major cost in building sewage treatment plant facilities. Two major methods presently used for treatment and disposal of sewage sludges are anaerobic digestion and incineration. Other methods such as burial of dewatered sludge and application of un-dewatered sludge to farmland have severe limitations. When the problems involved with these presently used disposal methods are considered, a reduction of volume and weight would be very beneficial. Composting dewatered sewage sludge offers this possibility.

Composting of organic matter such as garbage has been practiced for many years. Composting can be defined as decomposition of organic waste by aerobic thermophilic organisms to produce a stable humus-like material. The byproducts of this treatment process are carbon dioxide, water, and heat. The compost produced can be used effectively as a soil conditioner with a fertilizer value about the same as cattle manure, or as innocuous, odor-free landfill that does not need additional cover material.

Composting of refuse has had many problems. Some of these problems are associated with the costs of separating and grinding large volumes of refuse and obtaining a market for the final product to offset some of the costs of disposal. The treatment of a combination of refuse and sewage sludge by composting is presently being studied and used.[1, 2] The addition of sewage sludge to refuse composting is said to accelerate the decomposition and improve the final compost.[3] It is commonly accepted that dewatered sludge (containing 70% moisture) from a community represents only about 15 percent by weight of the total solids disposal problem. The work completed in this study illustrates the ability of composting to effectively treat dewatered sewage sludge *alone* to produce a stable, hygienic material.

Scope of Work

Composting of sewage sludge alone is a new approach to a very old problem. Preliminary work indicated that weight, volume, and solids reduction by this treatment method appeared very attractive. On the basis of favorable results from preliminary work, a project proposal was prepared. This project was funded by the Bureau of Solid Waste Management as a research contract. The test program was designed to obtain the following basic information concerning the composting of a combination of primary and secondary dewatered sewage sludges: (1) effect of mixing; (2) effect of moisture content; (3) effect of recycling; (4) process capacity; (5) air requirements; (6) effect of chemicals used for conditioning the sludge for dewatering; (7) composition of off-gases; (8) destruction of pathogenic bacteria, fungi, nematodes, and viruses; and (9) chemical and physical composition of the final compost.

All of the 16-month study, except that related to the destruction of pathogenic organisms, was performed by The Eimco Corporation Sanitary Engineering Research and Development staff under Director A. A. Kalinske. The work on the destruction of pathogenic organisms was performed at the University of Utah, School of Medicine, Department of Microbiology, under the direction of Dr. Bill Wiley.

Process Description

Composting, as defined earlier, is an aerobic thermophilic biological process. As in any aerobic biological process, an adequate method for providing oxygen and thorough mixing are required to obtain efficient odor-free treatment. Composting of sewage sludge, as studied here, necessitated three phases of operation: dewatering the sewage sludge, mechanical composting, and final curing. Each of these phases is described with reference to a flow diagram (Figure 1), and the dewatered sewage sludge was fed to the composter as indicated in the Feeding Schedule.

Dewatering the Sewage Sludge

The sludge used during this study was a combination of primary and two-stage trickling-filter secondary sludge from the Salt Lake City Sewage Treatment Plant. The sludge was obtained each day and stored in a 350-gal storage tank. Before vacuum filtration, the sludge was conditioned with ferric chloride and lime or a polymer to aid filtration. The sludge was then dewatered on a vacuum filter and the cake was ready for feeding to the composter.

Feeding Schedule

Dewatered sewage-sludge filter cake was fed into the composter 8 to 10 hr per day, 6 days per week. This schedule was chosen to approximate the feeding schedule that would probably be encountered in most small-size sewage treatment plants. Most smaller plants filter during only part of each day and accumulate sludge the remaining time. Six days of operating data were averaged to present results on a weekly basis. No feeding or data collection were made on Sundays.

Mechnical Composting

The dewatered sludge was then mixed with recycled compost from the composter to adjust the moisture content and to thoroughly seed the incoming sludge with aerobic thermophilic microorganisms. This mixing was accomplished in a screw conveyor used to feed the composter. The combination of sludge filter cake and recycled compost then entered the mechanical composter where it was continually mixed (by paddle mixers) and aerated for about 20 days or more depending on the final volume of compost removed from the composter. As the result of biological action during the composting period, the temperature of the mixed bed averaged about 140 F.

Final Curing

Each day the final product from the composter was stored in an individual pile, and it was then observed for 2 weeks.

Description of the Pilot Plant

The pilot plant was located at the Salt Lake City Sewage Treatment Plant inside the digester heat-exchanger building (Figure 2). A pipeline was connected to the plant's main sludge line, which went from the primary clarifiers to the digesters. Sludge was drawn from this line by line pressure to fill a 350-gal storage tank. This storage capacity represents about 500 lb of filter cake having 70 percent moisture.

The sludge was then continuously pumped with a variable-speed Moyno* pump from the storage tank to a flocculator. The pumping rate was varied according to the capacity of the vacuum filter to dewater the sludge.

The flocculator consisted of a 20-gal baffled tank having a variable-speed, 6-in.-diameter propeller. Chemical conditioners (lime and ferric chloride or polymer) were fed into the floc-

*Mention of commercial products throughout this report does not imply endorsement by the U.S. Public Health Service.

culator by metering pumps. The ferric chloride and lime were added to the sludge to give a content of 4.5 and 15.5 percent, respectively (based on sludge dry solids). Polymer was used in later tests and was added to the sludge to give a content of 1.6 percent on the same basis. The conditioned sludge then overflowed into the vacuum filter where it was dewatered.

The vacuum filter consisted of a vacuum pump, filtrate receivers and pumps, and the filter itself. The filter drum was 3 ft in diameter and 1 ft wide, with an effective filtration area of 9.4 sq ft. It was operated at a 30 percent drum submergence and at an average drum speed of 8 mpr (minutes per revolution). During cake formation, the vacuum was maintained at 12 to 15 in. of mercury and during drying, at 22 to 23 in. of mercury. The filter cake was discharged into a screw conveyor that moved the cake to a collection drum. At 30-min intervals, a portion of the collected filter cake was weighed and dumped into a second screw conveyor. At the same time, a portion of composted sludge was also weighed, recycled, and mixed with the filter cake with the use of the same screw conveyor.

The mechanical composter consisted of an open-top vessel having outside dimensions of 4 by 4 by 4 ft (40-cu-ft effective volume), a porous carborundum bottom, and four 20-in.-diameter paddle mixers rotating at 9 rpm. The inside of the composter was baffled and shaped to minimize cake packing to the sides and corners and to prevent short-circuiting. Steel fingers were attached to the inside walls to make the mixers self-cleaning. A double lobe-type blower supplied air to the composter; an orifice-manometer system employing water in the manometer measured the air; and a mercury manometer measured line pressure.

The operating level of the composter was maintained at a selected reference level. Each morning, before feeding, compost was removed, weighed, and placed in a storage pile for observation. The amount removed each day was determined by reducing the compost bed level to the reference level. If the initial bed level was below

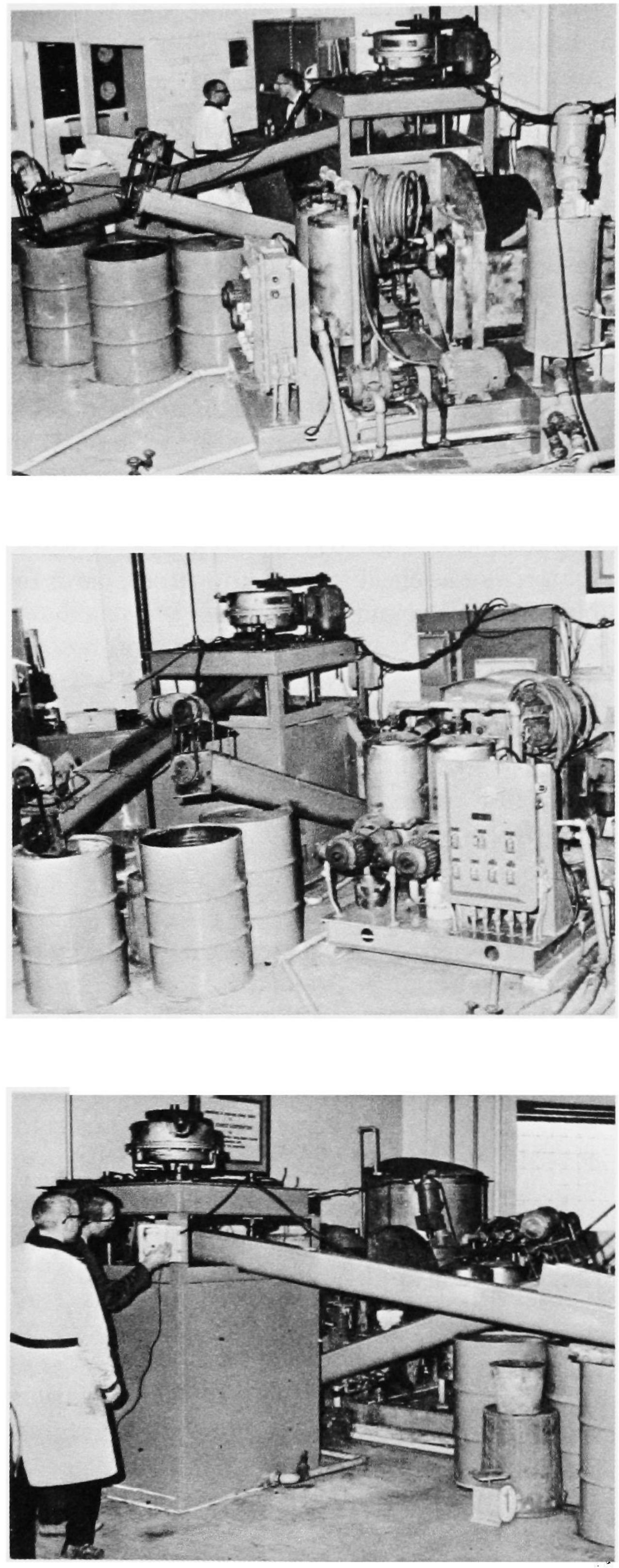

FIGURE 2. Compost pilot plant.

the reference level, no compost was removed. The effluent compost was stored in an outdoor area, and each area was marked and dated for further observations.

Test Techniques

Sampling and data collection for the following tests were conducted twice daily except for compost temperature and power readings. Compost temperature data were taken 4 to 10 times daily, and power data were measured once each week. Samples of compost were taken at the outflow of the composter, whereas filter cake samples were taken directly from the filter discharge. Both types were discrete (grab) samples. The application of each test technique to the tested materials was checked with known standards for both feasibility and accuracy.

Temperature

Temperature of the compost was measured with a Weston dial-type, all-metal thermometer, 0 to 220 F range; the stem was penetrated 6 in. into the compost bed for 5 min.

Volatile Solids

Volatile solids analyses were carried out by the procedure given in *Standard Methods for the Analysis of Water and Waste Water* [4] with one modification: ignition time of the sample was extended to a minimum of 4 hr.

Measurements for pH

Measurements were made for pH with Hydrion indicator paper in the appropriate range for each application.

Moisture

Percent moisture by weight determinations were made with an Ohaus moisture determination balance.

Bulk Density

Bulk density was measured with an accurately measured, 5-gal bucket that was filled with material and weighed. Bulk density was then calculated from the weight of the material divided by the volume of the bucket and expressed as pounds per cubic foot.

Total Weight and Volume

All materials fed, recycled, or wasted were weighed in a tared 5-gal bucket and recorded to determine total weight of each. Total volume of each was determined by dividing the total weight by its respective average bulk density.

Air Flow

Air flow was measured with a 1.764-in.-diameter orifice in a 3-in.-diameter pipe. Pressure differential across the orifice was measured with a water manometer. A mercury manometer downstream from the orifice indicated line pressure. All readings were corrected to 60 F and 1 atmosphere and expressed as standard cubic feet per minute (scfm).

Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen was determined with a Lavconco Micro Kjeldahl digestor and Micro Kjeldahl distillation unit. Standard procedures for the analysis of water and waste water [4] were followed, but micro amounts, as described in Scott's *Standard Methods of Chemical Analysis*, were used.[5]

Phosphorus

Phosphorus was calculated from determinations made for total phosphate following procedures given in *Standard Methods for the Analysis of Water and Waste Water* for the aminonaptholsulfonic acid method.[4] Results were expressed as phosphorus pentoxide.

Gas Analysis

A 10-ml disposable syringe was employed to take gas samples from the compost mass and from off gases. The syringe was flushed several times in the area from which the gas sample was to be taken to remove any residual gases. The sample was then pulled into the syringe and immediately sealed by pushing the needle into a rubber stopper while ejecting a small portion of the sample collected. This technique avoided contamination by atmospheric air. The same technique was used to inject the sample into the gas chromatograph. The gas samples were then analyzed for oxygen, nitrogen, and carbon dioxide on a volumetric basis with a Varian Aerograph model 90–P3 gas chromatograph with a two-column separation technique employing dry, purified helium as the carrier gas. The first column, which consisted of 30 percent bis-2-2-(methoxyethoxy) ethyl ether on 45/60 Chromasorb P, separated carbon dioxide and hydrogen sulfide from the other components. The second column, which consisted of 10 percent 5A and 90 percent 13X molecular sieve carbonate material, separated the remaining components into oxygen, nitrogen, methane, and carbon monoxide. All values recorded were corrected to take into account the inert gases present (mainly argon) but not detected.

Power

A Weston Analyzer was used to observe the power required for mixing the compost; this was recorded as kilowatts.

Composting Process

Many factors played important parts in the treatment process studied. The effect of each of these factors on the overall results obtained was considered.

Mixing

Because of the high organic content of the dewatered sludge (requiring much oxygen) and its tendency to pack, continuous mixing was necessary. The major problem was to find a mixer so designed that it would not plug but would tend to lift and loosen the material. The ribbon augers that were tried initially clogged rapidly. Several modifications of these augers were tried without success. Finally, paddles, slightly angled so that lifting would occur, were attached to the drive shaft. Mixing appeared satisfactory, and later testing proved it to be good.

Because the compost had a tendency to pack, dead areas and clearances between the mixer and side walls and bottom had to be minimized. This was done by shaping the internal part of the composter as closely as possible to that of the mixers.

Wearing of the mixer paddles indicated that the abrasive qualities of the compost material were significant. A great deal of wear occurred on the mild steel paddles during a 3-month run. The environment in the compost bed was also conducive to corrosion; moisture, heat, and oxygen promoted corrosion and aggravated the wearing problem.

In composting garbage and refuse, mixing and aeration are used intermittently. In this study, both mixing and aeration were continuous. Tests were made to determine if continuous mixing was required. Observations made when aeration alone was employed showed that the compost bed temperature began to drop within one-half hr. after mixing was stopped. It was believed that continuous mixing was required to keep the bed loose and to prevent channeling of air.

Several tests were made to determine the extent of mixing that occurred in the composter. In two separate tests, plastic cubes and cylinders (approximately 250) were placed in the feed to the composter. These materials were dispersed throughout the compost bed within 2 hr. This rapid dispersion was not due entirely to agitator mixing, but was also related to the amount of compost recycled. The higher the recycle volume, the more completely mixed was the compost bed. As described later, a high recycle volume was very beneficial to the treatment process.

Moisture Content

Moisture content of the filter cake and the compost was determined daily during this study.

The moisture content of the dewatered sewage sludge depended upon the discharge characteristics of the vacuum filter, the raw sewage sludge characteristics, and the chemical conditioners used. The moisture content of the compost depended upon the filter cake moisture, retention time within the composter, and the rate of the aeration and mixing.

When ferric chloride and lime were added for conditioning at values of 4.5 and 15.5 percent, respectively (based on sludge dry solids), the filter cake had a moisture content of 68 to 74 percent and the material was easily handled and conveyed. Filter cake conditioned with Rohm and Haas C–7 to give a content of 1.6 percent (based on sludge dry solids) had an average moisture content of 77 percent. A moisture content of 70 percent can be realized with polymers, but this would require a more complex application technique.

Moisture content in the composter ranged from 20 to 35 percent with an average of 26 percent. The moisture content, as stated before, depended on many variables, all of which may be controlled to some degree. The amount of filter cake and its moisture content determined the quantity of moisture entering the composter

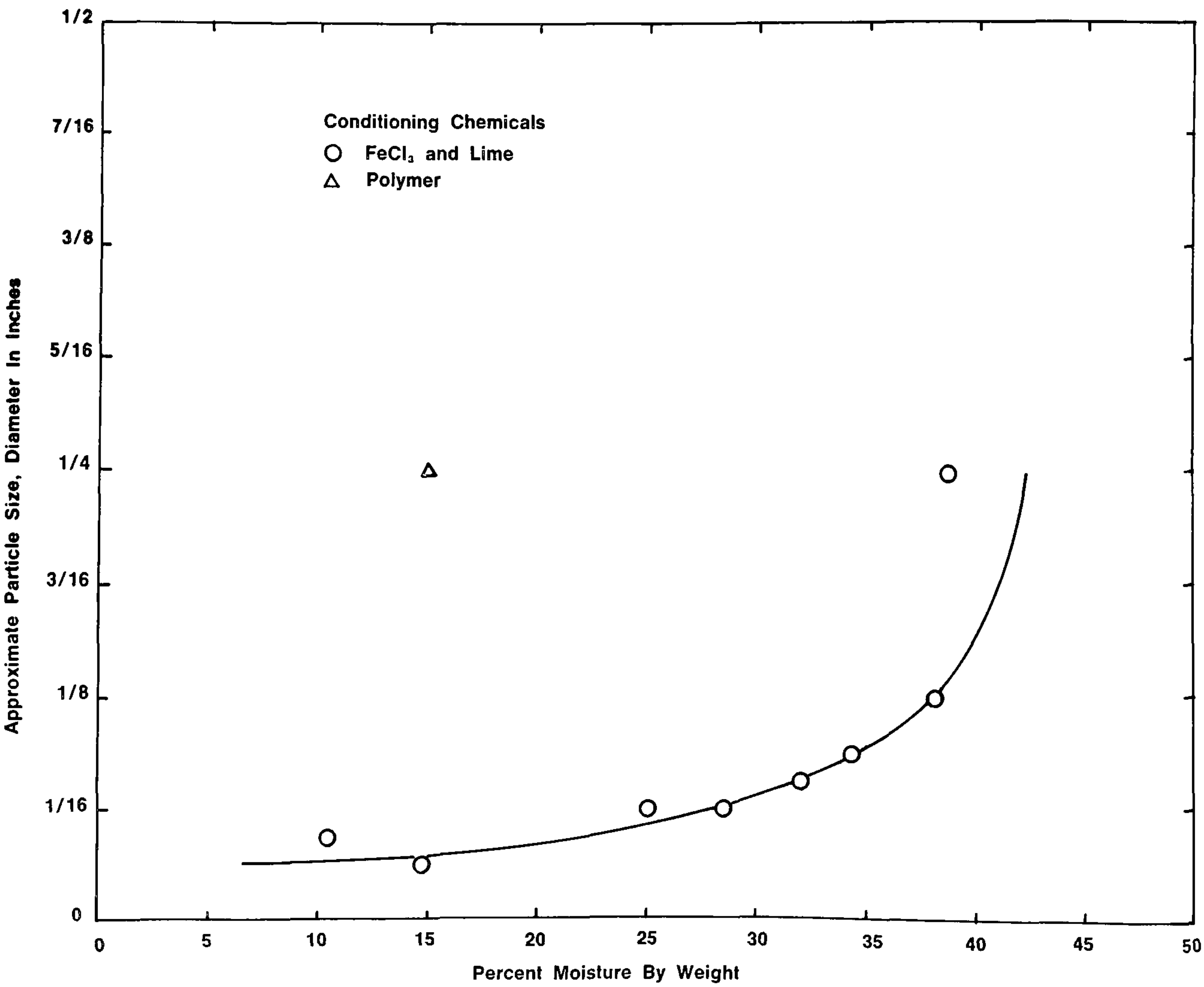

FIGURE 3. Effect of moisture on compost particle size.

daily. Retention time and rate of aeration affected the degree of evaporative drying.

Moisture content of the feed to the composter depended on filter-cake and recycled-compost moisture and their relative quantities. Based on filter-cake moisture of 72 percent, recycled-compost moisture of 26 percent, and a recycle ratio of 1.5, an input moisture of 45 percent could be expected.

Moisture content of the recycled compost and filter cake was a major process limitation. Moisture content controlled particle size of the compost (Figure 3). This factor greatly affected process efficiency. Effective mixing within the composter was achieved only when the particle size of the compost was less than 1/8 inch. Mixing of recycled compost and filter cake was also affected in the same manner. Recycled compost of low moisture content (26 percent) and small particle size (1/8 inch) when combined with filter cake (72 percent moisture) produced a feed material easily mixed in the composter. If the recycled compost were insufficient and contained a high moisture content, the combination of recycled compost and filter cake would result in a sticky mass difficult to mix in the composter.

The biological action of the microorganisms present in the composter, as indicated by temperature, was affected by moisture. Temperature was greatest at moisture contents of 20 to 30 percent and near nonexistent at moistures above 40 percent or below 15 percent.

The extremes of moisture content, high and low, created physical problems related to the operation of the process. If the average moisture content of the compost mass exceeded 35 percent, the compost mass would begin to ball and clump together. This, of course, produced a mixing and aerating problem. Moisture content of the compost mass of 15 percent or less created a dusting problem because the forced aeration caused fine particles of compost to exhaust from the composter.

Recycling

Recycling of compost has several positive effects on this treatment process. The first, and probably most important, is the effect of the composter feed on the moisture content. If recycling were not used, the moisture content of the composter feed would be that of the sludge filter cake, and mixing problems (balling and packing) would develop. As was pointed out earlier, a feed moisture content of 45 percent or less can be obtained using a 1.5 recycle ratio when the filter cake has 72 percent moisture. When feed to the composter was consistently over 50 percent moisture, mixing problems soon developed.

Another benefit of recycling is that the feed to the composter is thoroughly seeded with aerobic thermophilic microorganisms, and the biological activity is rapidly started, e.g., a 45 percent total solids reduction at 1.5 recycle ratio compared with an 18 percent total solids reduction at 1.0 recycle ratio, both at a 7-day retention time (based on the volume of dewatered sludge fed daily) (Figure 4). This indicates, then, that recycling compost, which seeds the filter cake and mixes the composter contents, produces beneficial effects.

The sludge filter cake conditioned with polymer indicated the same results. At a 2.0 recycle ratio, total solids were reduced 45 percent, with a 10-day retention time; at a 1.5 recycle ratio, they were reduced 43 percent, but with a 13-day retention time. The polymer-conditioned filter cake required more recycle than did the filter cake conditioned with lime and ferric chloride. This was because the polymer-conditioned filter cake contained 5 to 7 percent more moisture.

Recycling also increased the temperature of the feed from 10 to 20 F above that of the filter cake when a recycle ratio of 1.0 to 2.0 was used. This was believed to have a beneficial effect on the rapid response of the process.

When the sludge was conditioned with lime and ferric chloride, the filter cake pH averaged 11.0. The pH of the compost averaged 6.5, and

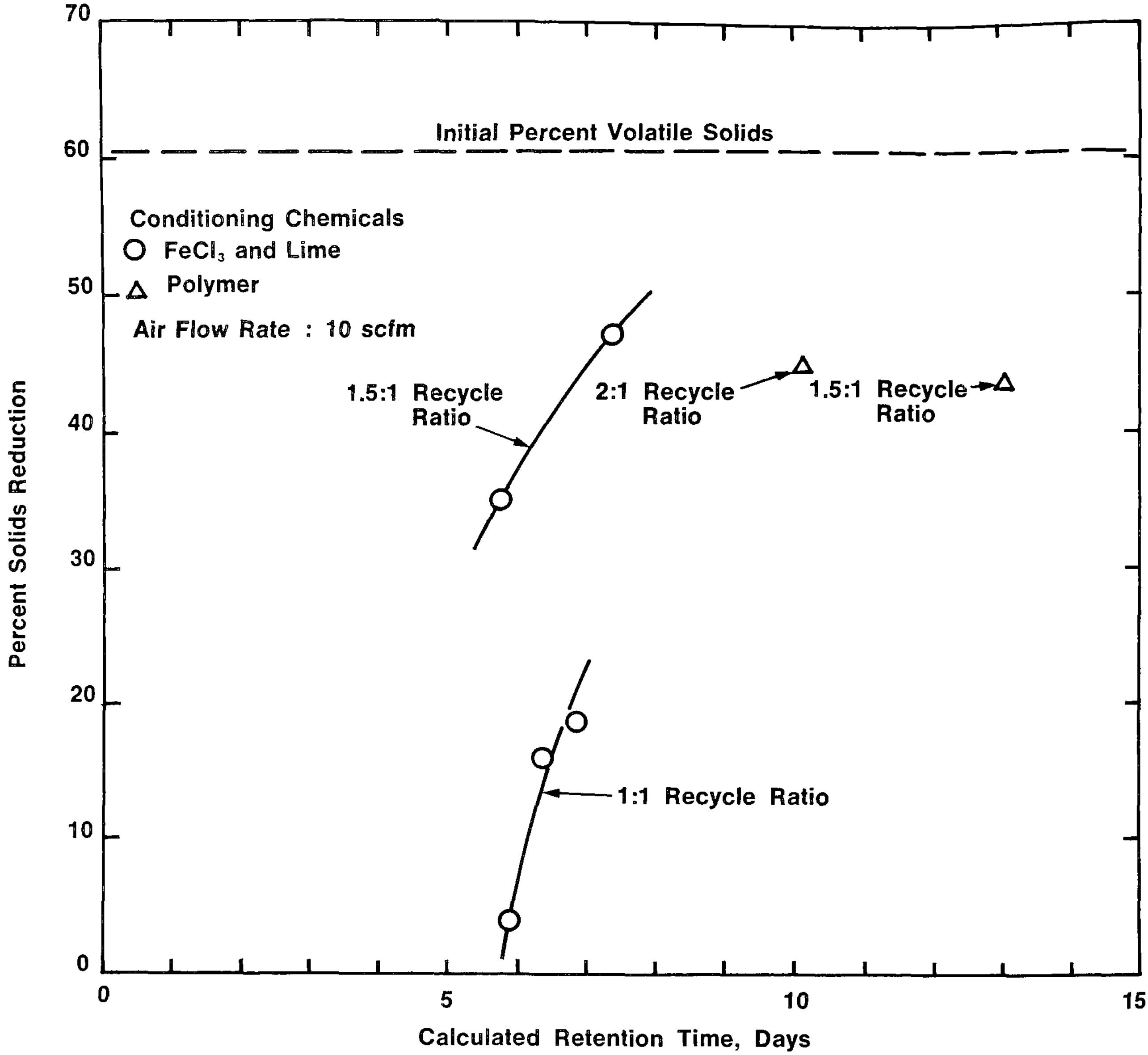

FIGURE 4. Effect of retention time on percent solids reduction.

therefore, it was probably beneficial to adjust the feed pH to be more compatible with the treatment pH by adding recycled compost to the feed.

Process Capacity

The ability of composting to stabilize the dewatered sludge and reduce its volume and weight was of major interest in the test program. The process consisted of evaporation (drying) and biological destruction of volatile solids by thermophilic microorganisms. Drying, which was explained under the discussion of mixing, is required not only for effective mixing, but because biological treatment is very slow to nonexistent at moisture contents above about 40 percent. Drying occurs in this process at a very rapid rate because of the high temperatures (140 F), continuous mixing, and aeration. The moisture content of the dewatered sludge, which averaged 72 percent, was reduced to an average of 26 percent in the final compost. This represents a total average weight reduction of 62 percent and a moisture reduction of 87 percent by weight by drying alone. The percent water reduction is limited to 98 percent (15% final moisture content) by the dusting problem stated earlier. The volume reduction from the drying process because of shrinkage would probably account for more than 75 percent of the total volume reduction.

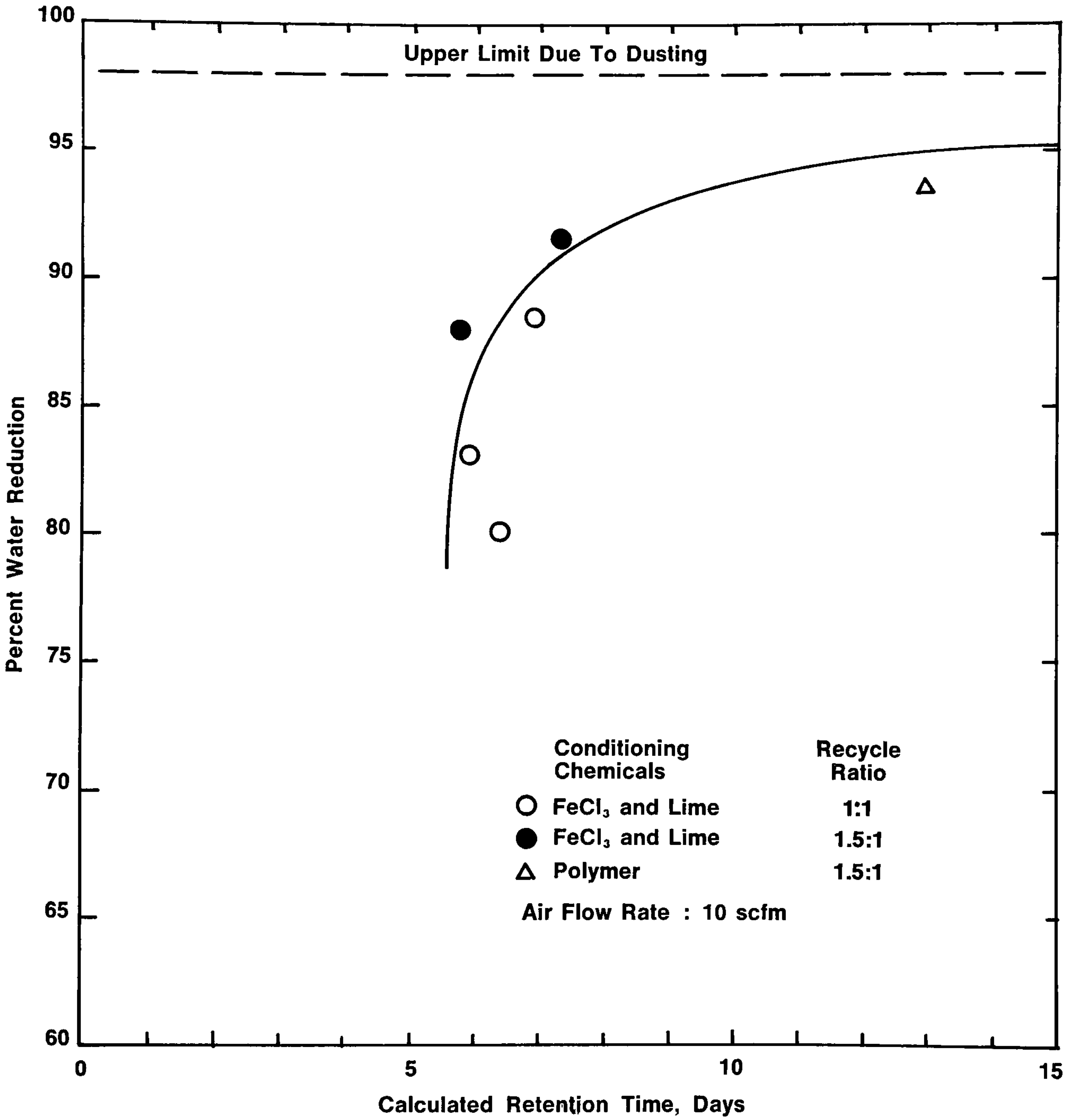

FIGURE 5. Effect of retention time on percent water reduction.

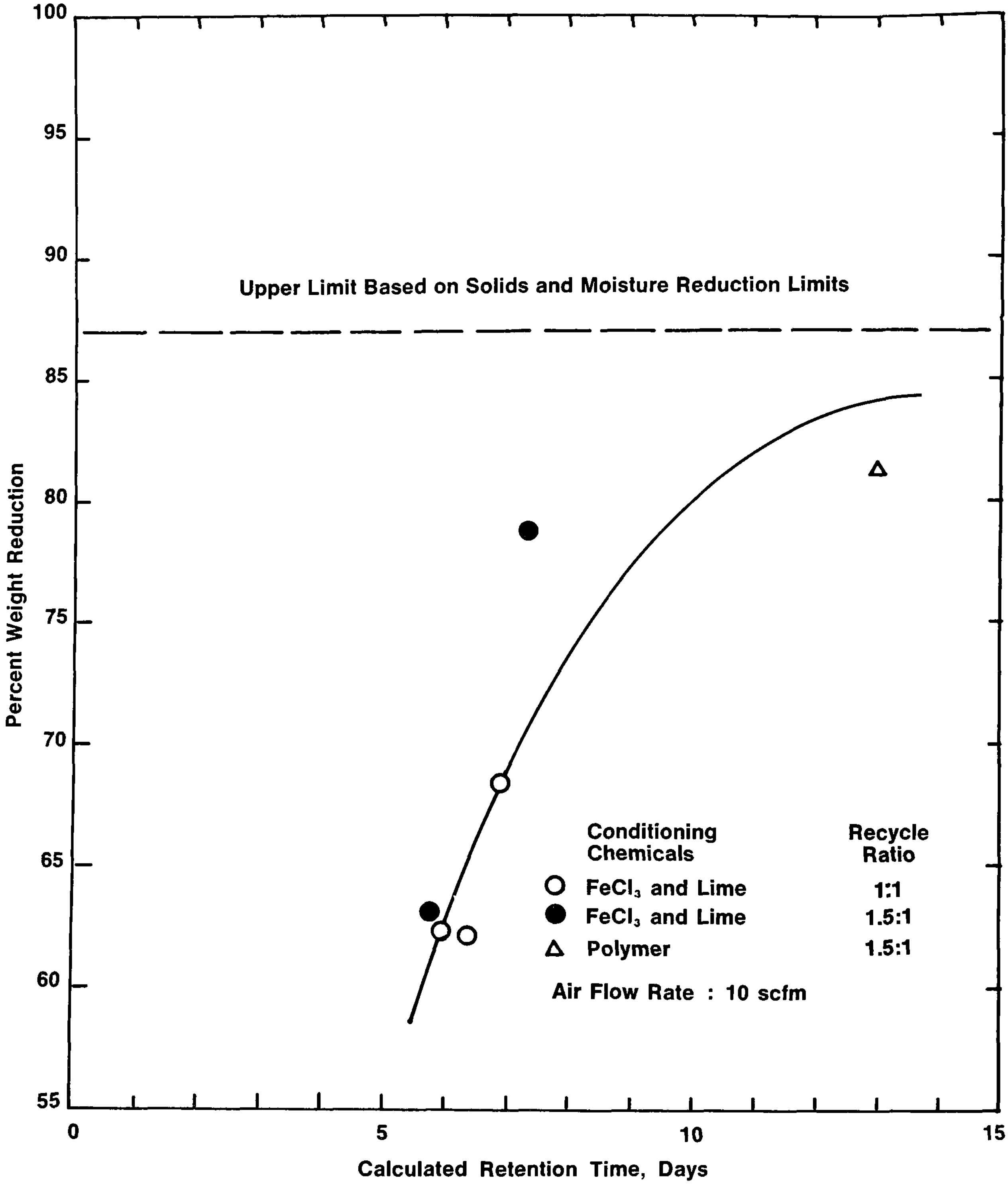

FIGURE 6. Effect of retention time on percent weight reduction.

Destruction of volatile solids by biological action of thermophilic microorganisms caused a reduction of both weight and volume, but more important, stabilized the dewatered sludge and made it hygienic and free of viable plant seeds. This part of the treatment process is most important from the standpoint of final disposal. The final compost is relatively stable organically, is hygienic, and can be used as a soil conditioner or as land fill.

The intensity of the biological process was indicated by the high compost-bed temperature maintained with continuous mixing and aeration, the change in pH from 11.0 to 6.5, and the reduction of solids. An average total-solids (inerts included) reduction of 30 percent and an average volatile-solids reduction of nearly 50 percent occurred in the process. Solids reduction is limited to 61 percent, which is the volatile-solids content of the feed.

Again, the amount of volume reduction that results from biological action is not known. The average total volume reduction was 73 percent. All of the above average data were based on a retention time of 7 days. To obtain the *calculated* retention time, divide the total active volume of the composter by the volume of unpacked dewatered sewage sludge fed daily. The *actual* retention time in the composter is much greater than the time indicated in the above calculations because of the gross reduction of volume occurring during the process. Whereas the calculated retention time for the above averages was 7 days, the actual average retention time was closer to 26 days. The relation of *calculated* retention time to the moisture, weight, and volume reduction is based on a comparison of filter cake with compost (Figures 5 to 7).

A flow diagram was made showing the fate of 100 lb of dewatered sewage sludge fed to the composter, with the amount of feed and products and their respective compositions (Figure 8).

Another factor influencing the rate of the composting process is the effect of the feed schedule. Intermittent feeding affected the compost-bed temperature; the bed temperature dropped about 15 F during a feed period of 10 hr (Figure 9). It is assumed that continuous feeding would be beneficial to the treatment process by providing more uniform operating conditions. Continuous feed may significantly reduce the calculated retention time by allowing an increase in the amount of feed while still producing the results observed during intermittent feeding used during this study.

Required Air

Forced aeration was applied to the compost bed (*See,* Pilot Plant Description), and flow rates were measured (*See,* Test Techniques).

Aeration of the compost bed served two main functions. The first function was to provide a means for rapid evaporation of excess moisture fed to the composter. The large volume of air required for drying was shown to be well in excess of the air required to maintain aerobic conditions, the second function of aeration. This point was demonstrated (Figure 5); the treatment process required a minimum 4-day calculated retention time before solids destruction occurred. If feed to the composter had been predried, probably less retention time would have been required.

From the large reduction in moisture (80 to 90% by weight) during the process and the retention time required for solids destruction, composting of dewatered sewage sludge is obviously first a process of evaporation and second, of biological destruction of volatile solids.

A straight line plot indicated that the efficiency of oxygen uptake in relation to air applied was not rate dependent on the oxygen concentration present in the range of air-flow rates used during this study (Figure 10).

An air-flow rate of 10 scfm was used during most of the study because it was sufficient for drying and did not excessively cool the bed. This rate represents a flow of 0.25 scfm per cut ft (based on 40-cu-ft volume) or 0.75 scfm per sq ft (based on 13.3-sq-ft area) to the compost bed.

Forced aeration had a cooling effect on the compost bed (Figure 11). The temperature of

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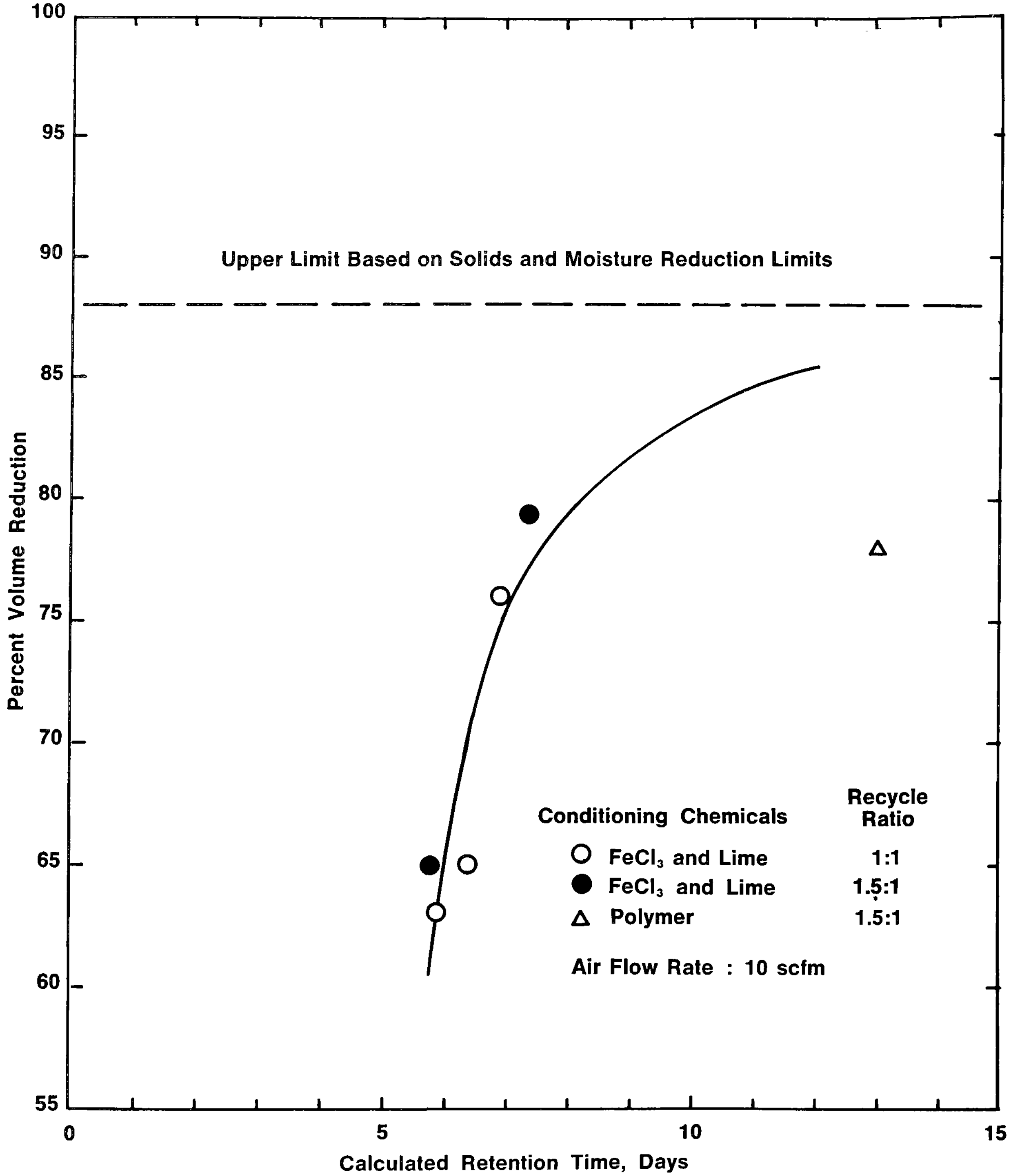

FIGURE 7. Effect of retention time on percent volume reduction.

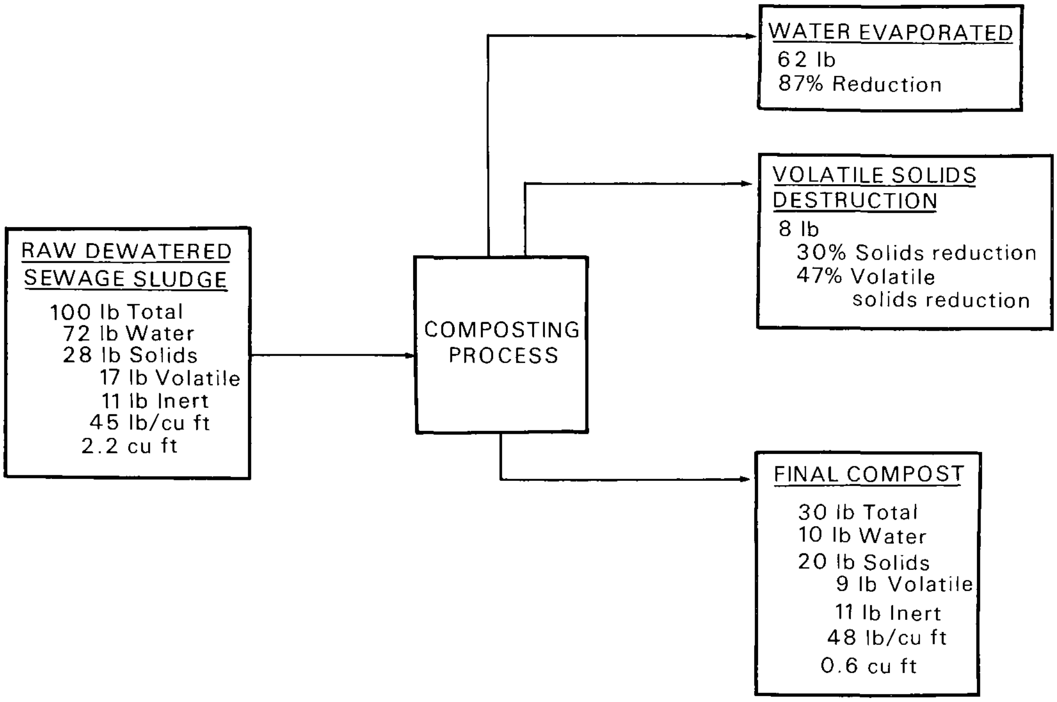

FIGURE 8. Dewatered sewage sludge composting—material balance.

the compost bed was recorded at four positions and three levels. (The position numbers are shown in a top view of the composter, and the levels noted indicate the distance from the bottom of the compost bed. A reading at the 6-in. level would be 6 in. upward from the bottom.) The three individual plots show that air rates up to 10.0 scfm did not lower the compost-bed temperature significantly. An average temperature decrease of 5 F was noted for air-flow rates between 5.3 and 10.0 scfm, and an additional 5 F decrease was observed for air-flow rates between 10.0 and 11.4 scfm.

The concentrations of oxygen and carbon dioxide in volume percent as a function of compost-bed depth are illustrated (Figures 12 and 13, respectively). These samples were taken at the same sampling points as the temperature data discussed above. Even at low air-flow rates of 3 and 5 scfm, more than 18 percent oxygen by volume was present at all times (air usually contains 21 percent oxygen by volume) (Figure 12). This again points to the fact that at the air-flow rates employed in this study, the oxygen concentration present was more than adequate at all times to maintain aerobic conditions. Also, as one would expect, the concentration of oxygen present in the air flowing through the bed was greatest at the highest air rate.

The concentration of carbon dioxide present in the air passing through the compost bed at varying air-flow rates is shown in Figure 13. The carbon dioxide concentration at an air-flow rate of 5.3 scfm was greater than that at 3.4 scfm. The explanation may be that the biological activity, as indicated by bed temperature, was greater in the compost bed during the run at 5.3 scfm and, hence, presumably more carbon dioxide was produced.

According to the oxygen used, the absolute values of carbon dioxide produced should be almost twice the concentrations shown in Figure 14. It was assumed that part of the carbon dioxide reacted with the excess lime present in the dewatered sewage sludge. Therefore, although the values recorded are not absolute, they do give an indication of process activity.

The lowest oxygen and highest carbon dioxide concentrations existed in the center of the compost bed (Figures 13 and 14). As fresh air fed to the bottom of the compost bed moves upward, oxygen is depleted and carbon dioxide is added. At a point somewhere between 18 and 30 in. (36-in. total bed depth) above the bottom of the compost bed, the effect of air diffusing downward from mechanical mixing occurred. From this point upward, the concentration of oxygen increased whereas the concentration of carbon dioxide decreased.

Influence of Conditioning Chemicals Used in Vacuum Filtration

Conditioning chemicals used before vacuum filtration or any liquid-solids separation process may be classified into two main categories: inorganic chemicals, such as ferric chloride and lime, and polymeric organic chemicals. This variable

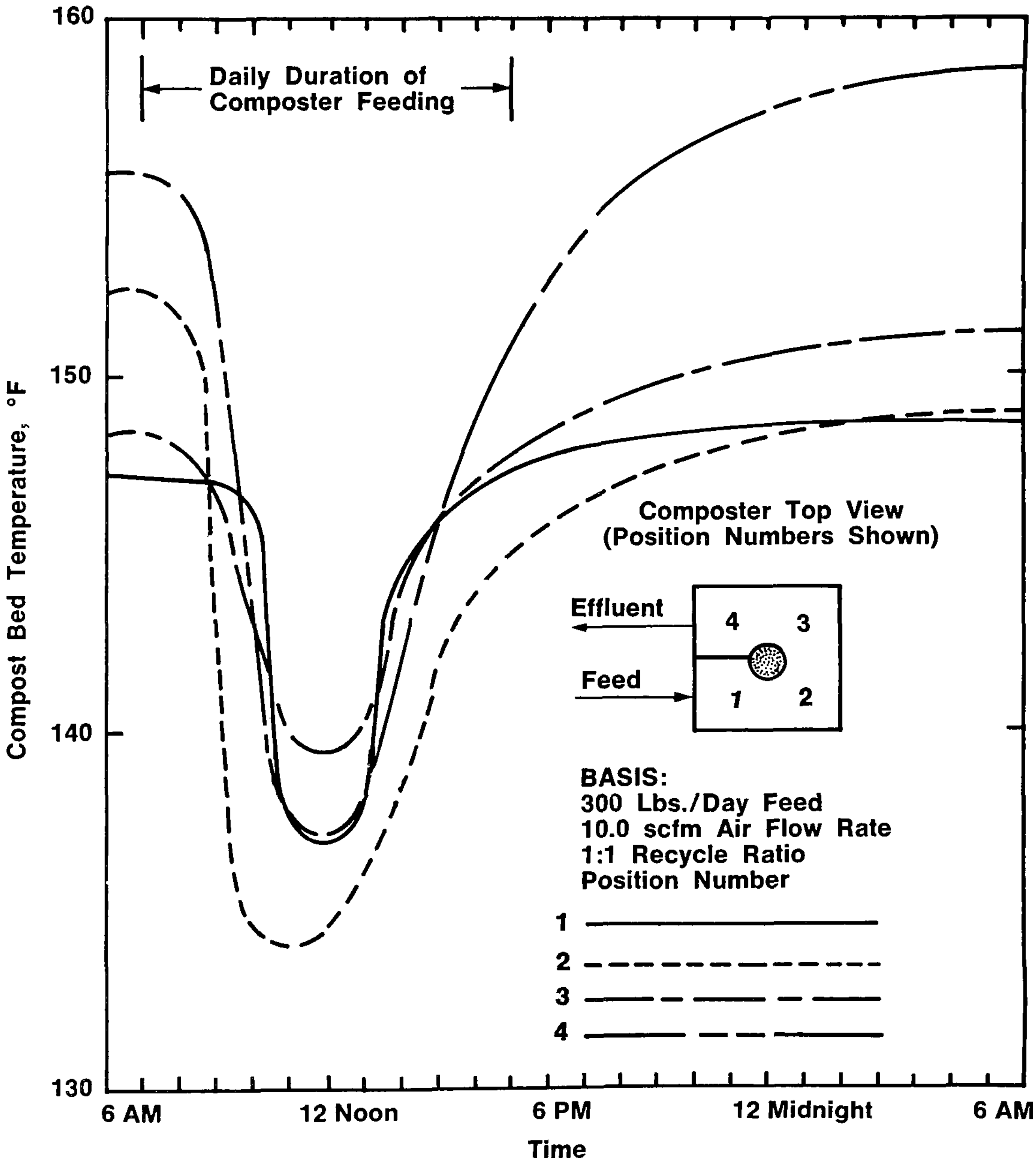

FIGURE 9. Effect of intermittent feeding on compost bed temperature.

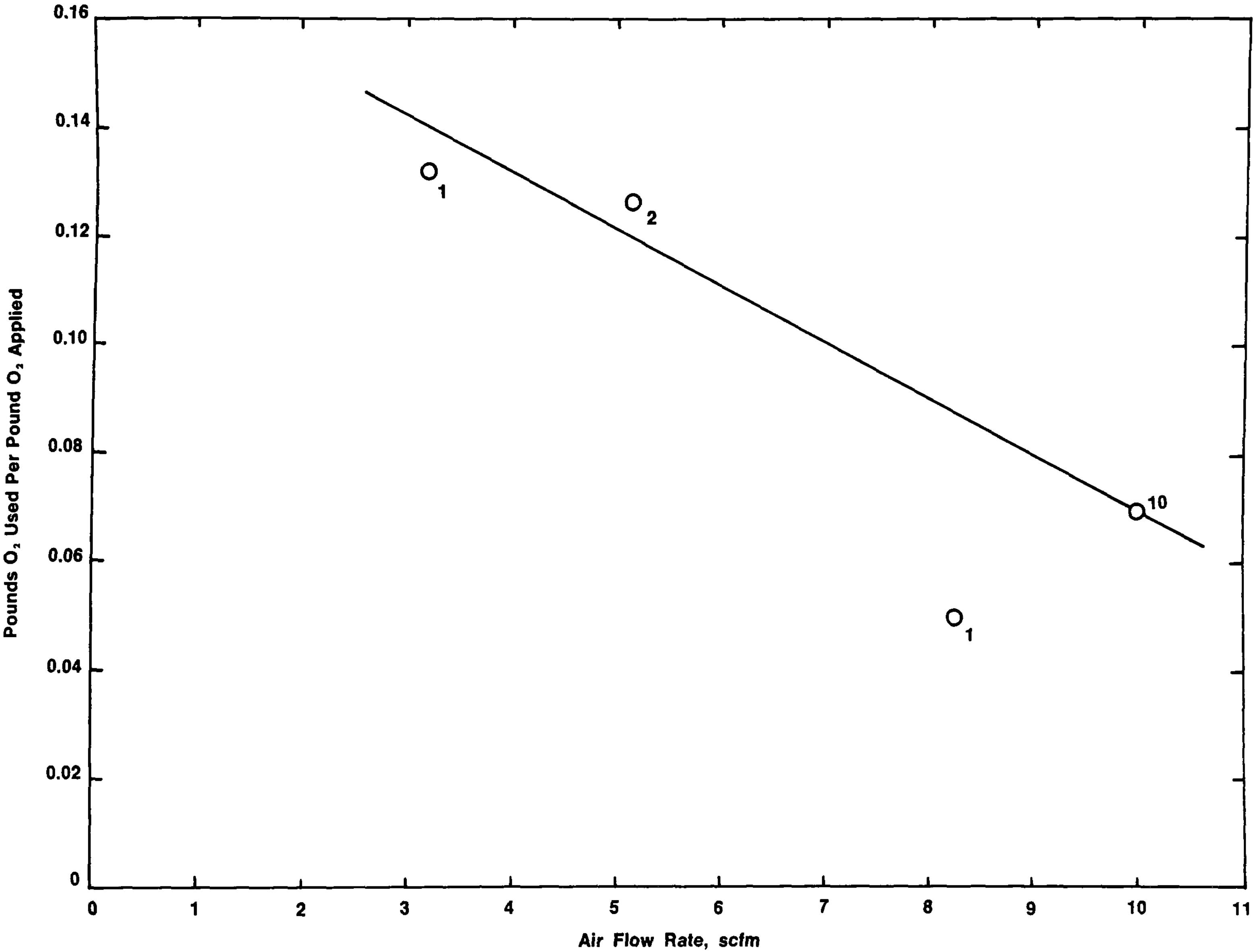

FIGURE 10. Efficiency of oxygen uptake rate. Numbers with data points indicate number of observations used to average each point.

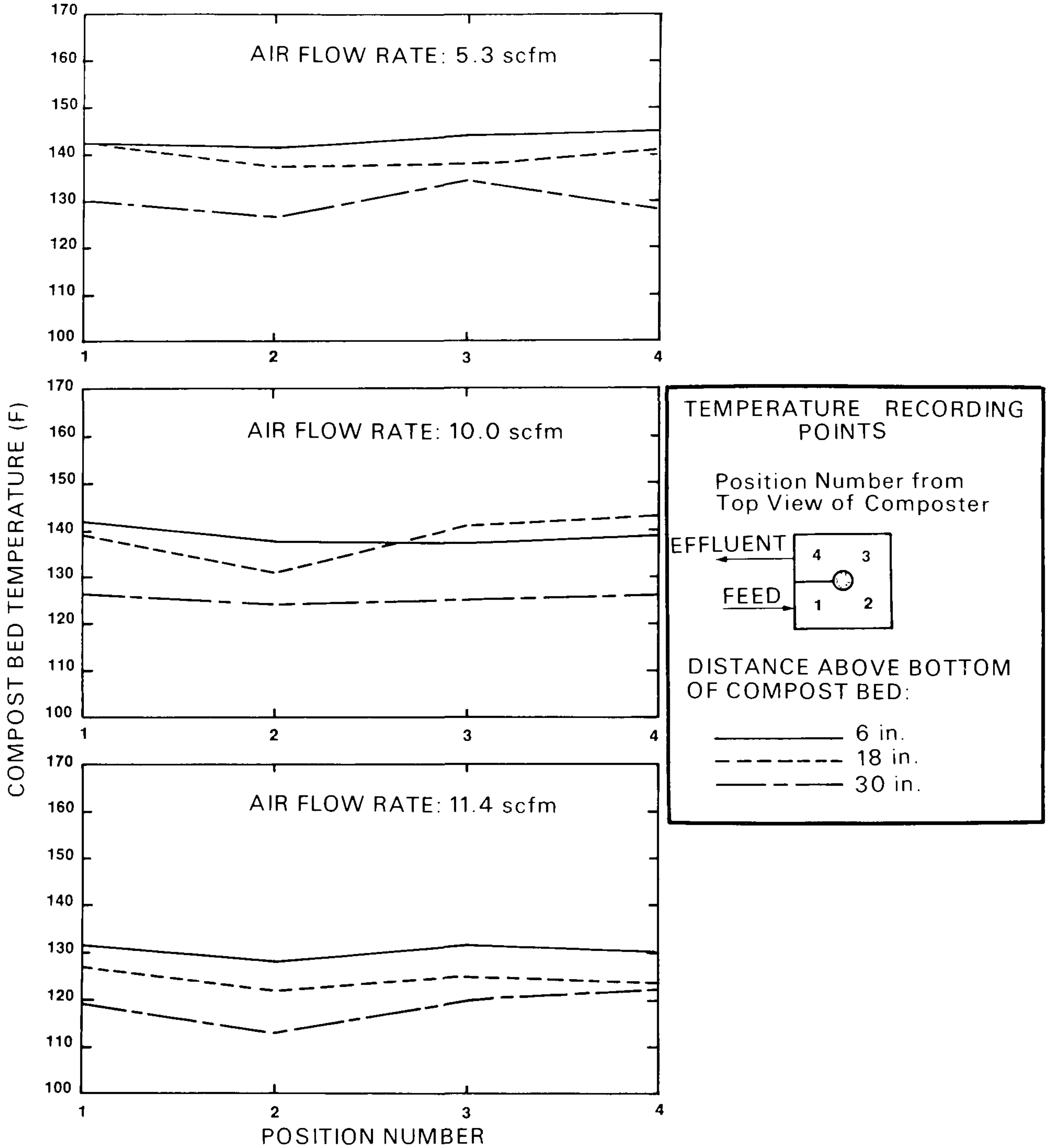

FIGURE 11. Effect of air flow rate on compost bed temperature.

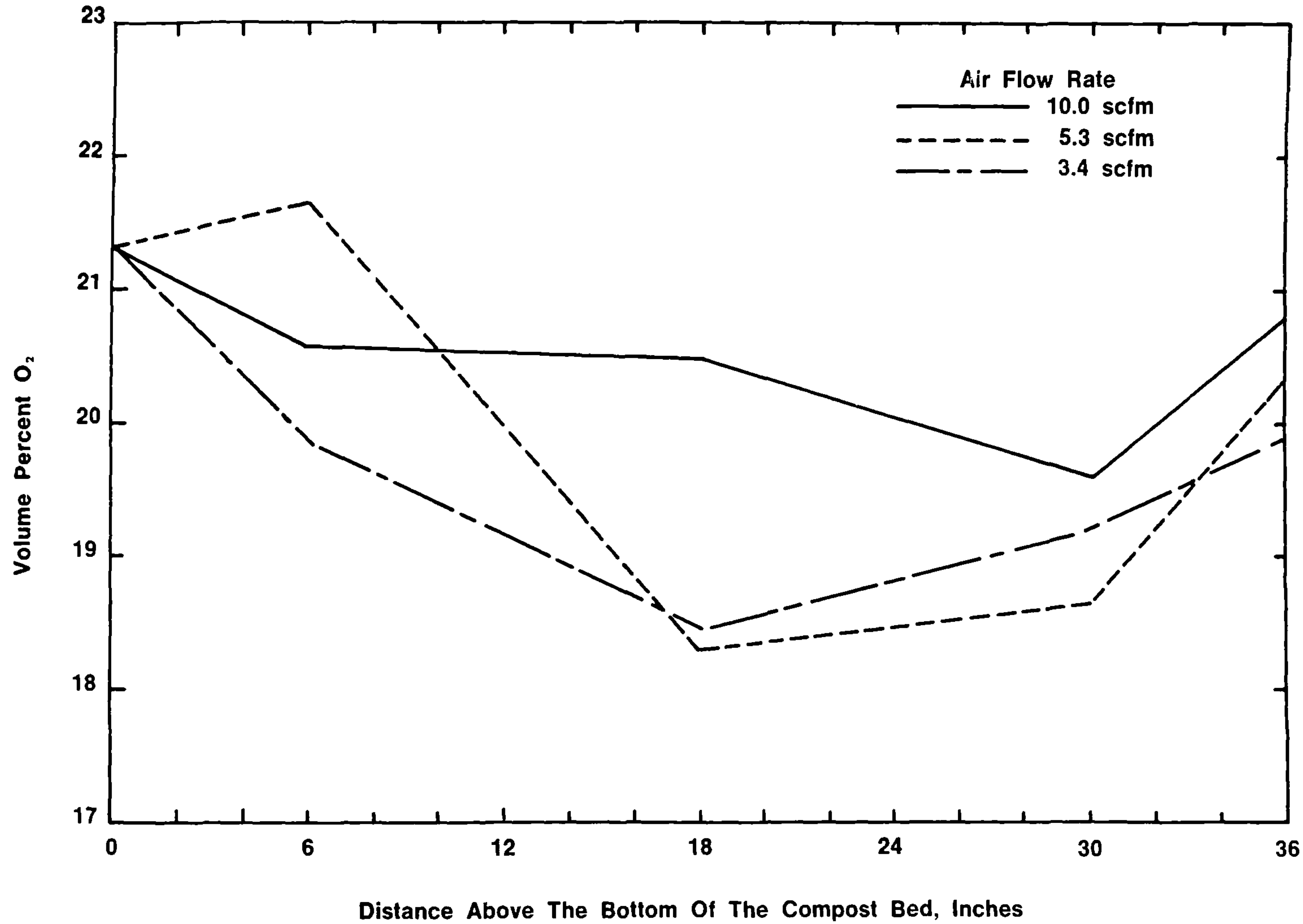

FIGURE 12. Effect of air flow rate on oxygen concentration. The total depth of the bed was 36 in.

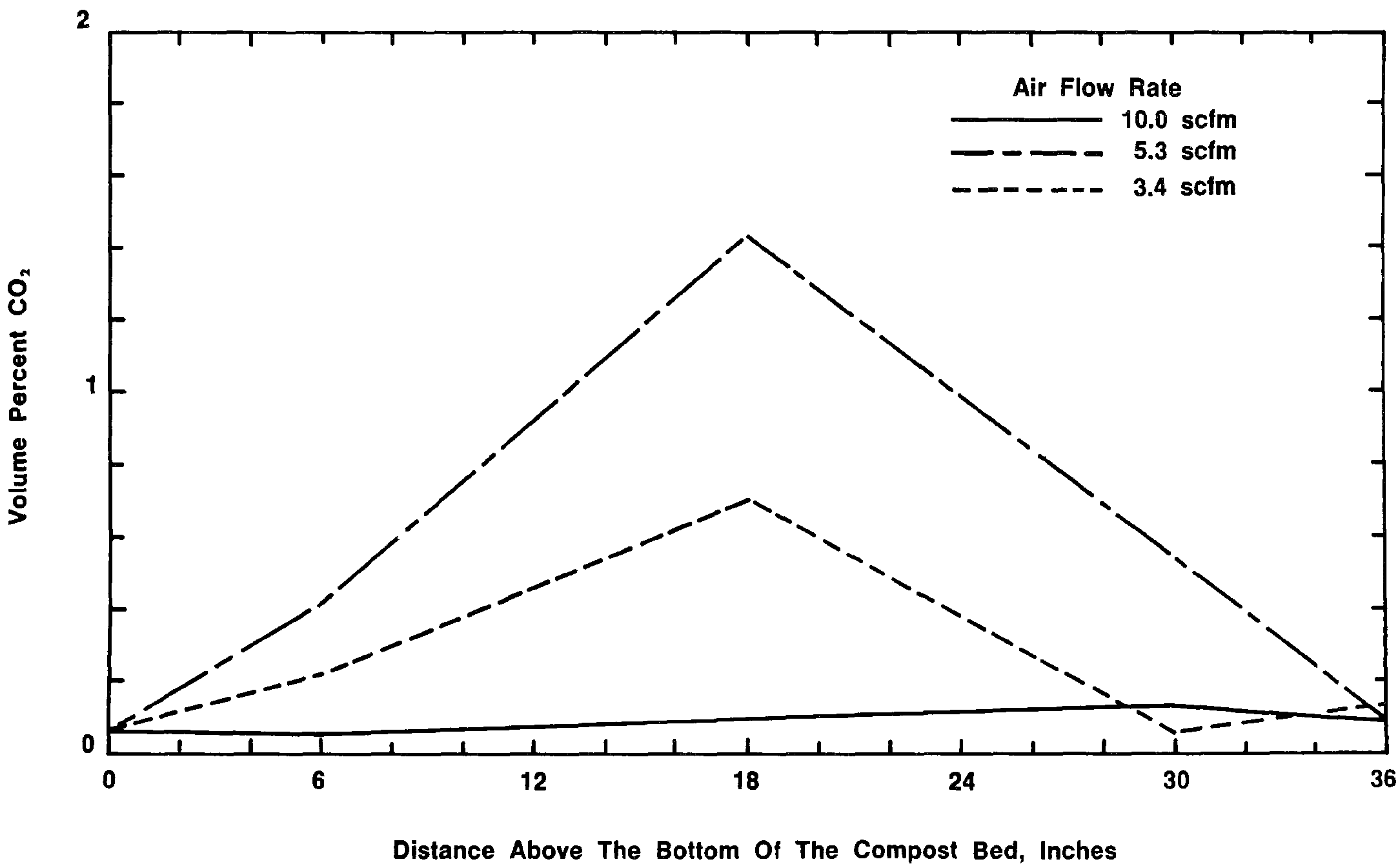

FIGURE 13. Effect of air flow rate on carbon dioxide concentration. The total depth of the bed was 36 in.

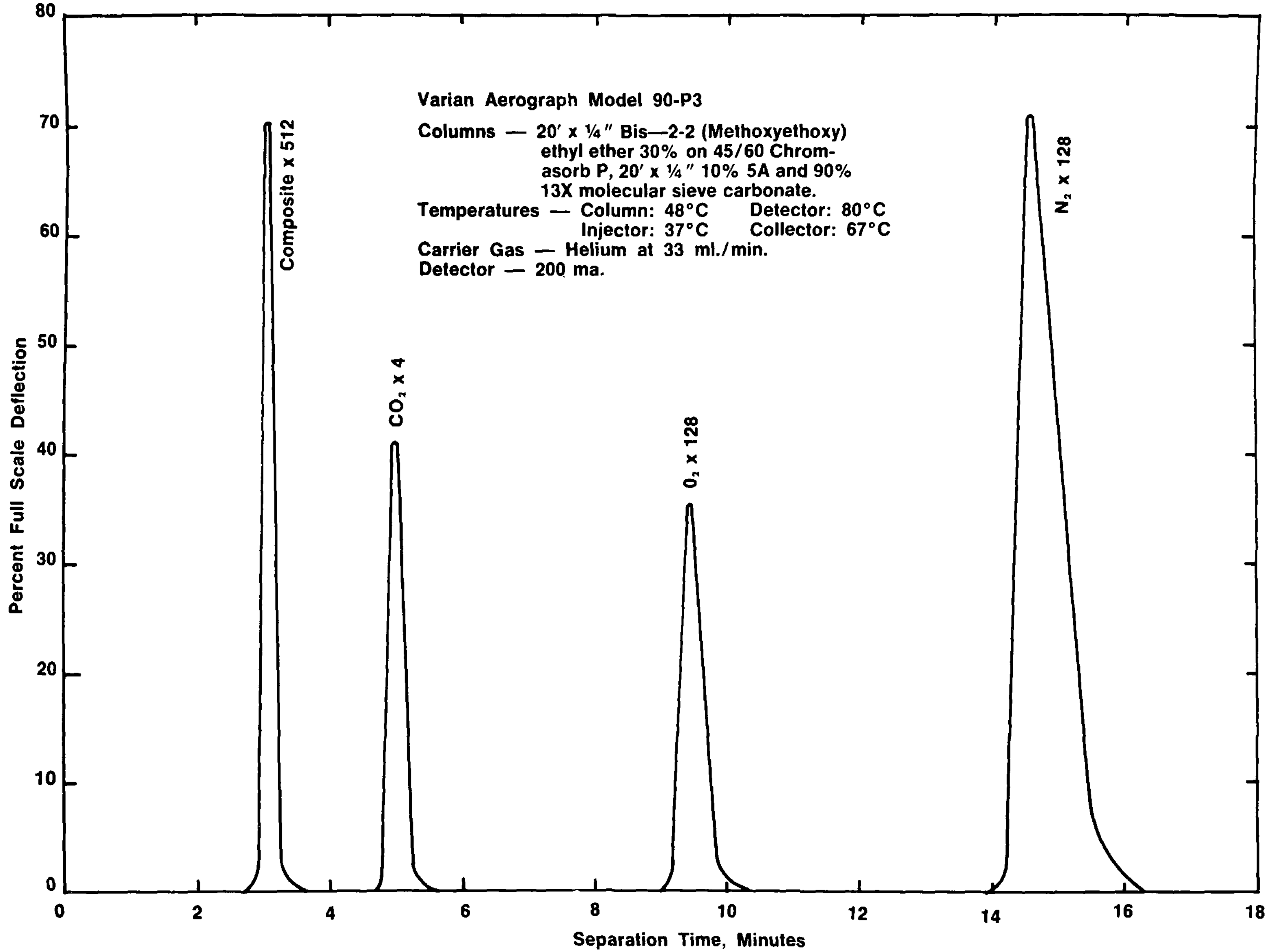

FIGURE 14. Gas chromatograph separation of composter off gases (below).

in the composting of dewatered sewage sludge was studied to observe any differences in the process attributable to the conditioning chemicals. There has been a trend toward the use of polymers as sludge conditioners because they are easy to handle.

Different sludge conditioning agents produce filter cakes with differing physical properties. Sewage sludge conditioned with ferric chloride and lime produced a very firm filter cake that discharged from the filter medium easily. The polymers, however, produced a filter cake that was sticky and difficult to discharge from the filter medium. The filter cake conditioned with polymer also contained about 5 percent more moisture. Although an increase in moisture may account for some difficulty in discharge of the filter cake from the filter medium, it would not account for it becoming sticky.

The above change in physical characteristics caused by the use of polymers resulted in many handling and mixing problems. Although the firm filter cake produced by ferric chloride and lime conditioning was easily conveyed by an inclined screw conveyor, polymer-conditioned filter cake produced a sticky, "clumpy" mass that was both difficult to convey and handle. The slight increase in moisture in the polymer filter cake may account for a portion of this problem, but does not totally explain it. A similar problem was also encountered in mixing the recycled compost material with the filter cake. The filter cake produced with ferric chloride and lime, with its firm consistency, mixed easily with the recycled compost and produced a satisfactory feed to the composter unit. This easy mixing facilitated a well-seeded feed to the composter. Mixing the sticky, polymer-conditioned filter cake and recycled compost was difficult and produced a "clumpy" mass to be fed into the composter. This "clumpy" mass was then also difficult to mix in the composter.

The sludge-conditioning agents used also changed other physical properties of the compost bed. The filter cake conditioned with ferric chloride and lime resulted in a compost bed resembling sawdust in consistency. It mixed easily and posed no handling problems. The compost bed of dewatered sewage sludge conditioned with polymers had a particle size of gravel (1 in. or less). One result of this increase in particle size when polymers were used was that the air-flow rate through the compost bed was necessarily reduced from 10 to 3 scfm. When the same air-flow rate was used with polymer as was used with ferric chloride and lime conditioning, the compost-bed temperature decreased by an average of 10 F. The change in particle size of the compost bed can only be accounted for by the change in chemicals used for conditioning because the compost bed contained the same or less moisture with the polymer than with ferric chloride and lime. This problem may be related to the bonding characteristics of the polymer as opposed to the powdery consistency of the inorganic chemicals used.

The final product and its disposal are also influenced by the conditioning chemicals. As stated before, the compost resulting from ferric chloride and lime filter cake was similar to sawdust in consistency. This material could easily be conveyed and disposed of in a variety of ways. The gravel-size material resulting from composting filter cake conditioned with polymers may have to be ground before final use or disposal.

Other than these physical characteristics, the other properties of the final product were about the same.

Off Gases

Off-gas samples were taken directly above the surface of the compost bed and analyzed (*See* Test Techniques). A typical gas chromatograph plot illustrates that the gas sample was split into well defined peaks and was easily measured (Figure 14).

The composition of gases passing through the compost bed and the off-gas concentrations of oxygen and carbon dioxide changed in volume percent (Figures 12 and 13). Oxygen concentration, even at low air-flow rates, did not drop below 20 percent at the compost-bed surface (Figure 12). Carbon dioxide concentration did not exceed 0.1 percent at the compost-bed surface (Figure 13). The values of carbon dioxide and oxygen concentration in the off gas should not be of concern.

Ammonia was detected during the time filter cake (conditioned with ferric chloride and lime) was fed to the composter. The strength of ammonia odor was in direct proportion to the rate the filter cake was fed. The ammonia quickly dissipated and created no problem. Ammonia was not detectable 2 hr after feeding was discontinued. A quantitative value of the am-

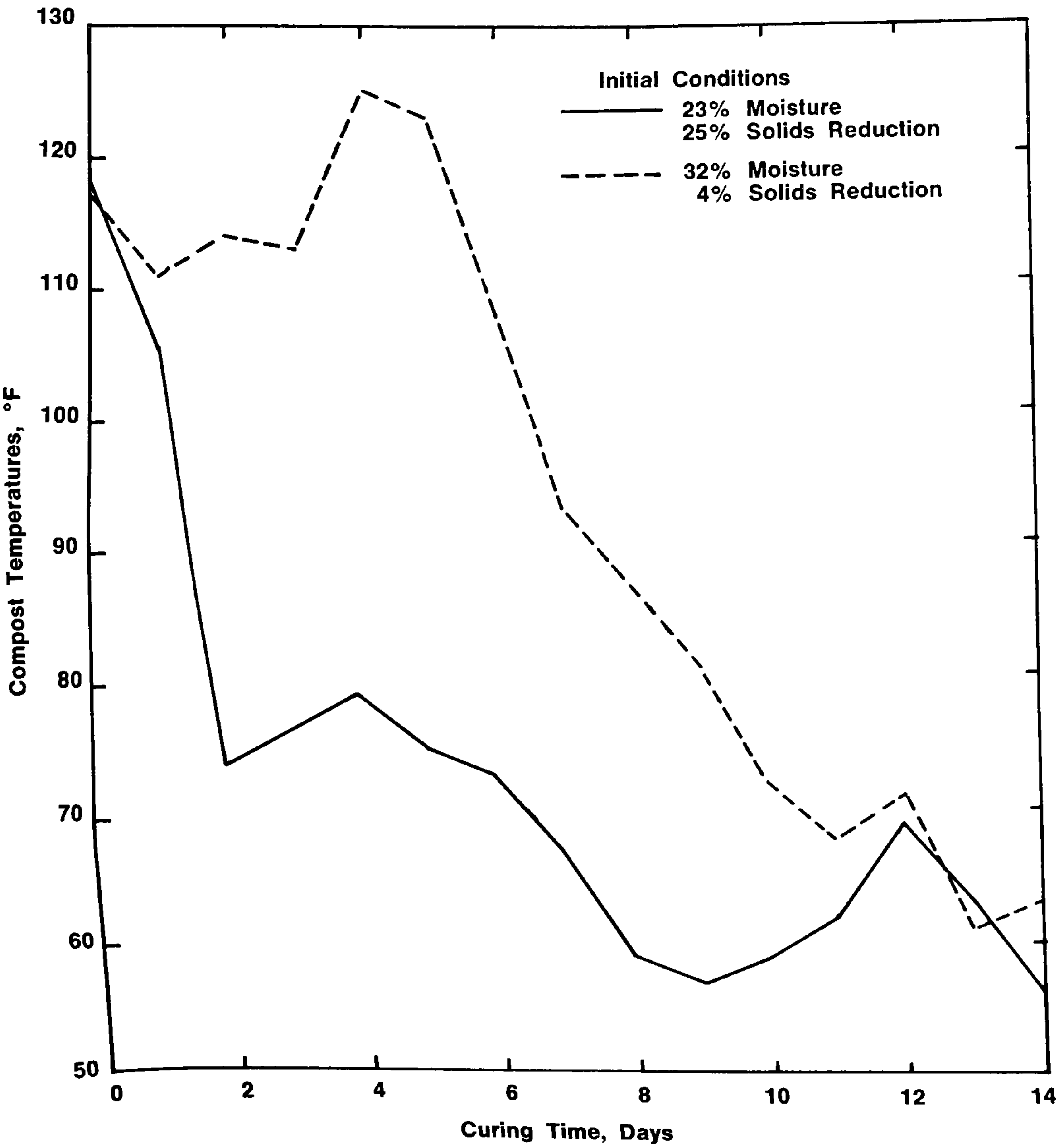

FIGURE 15. Time–temperature relationship in compost curing process.

monia concentration was not measured with the gas chromatograph because the equipment would need to have been changed for ammonia analysis and other gas analyses could *not* then have been determined. The applied air was believed to initially strip the ammonia (present because the pH was high when lime was used) from the compost. Although the gas chromatograph system was capable of detecting hydrogen sulfide, methane, and carbon monoxide, none of these gases was detected. These gases could have been present in trace amounts, but they were not detected by this analytical technique or by their odor.

The odor of the combined off gases resembled the odor of silage: a sweet, musty odor that might be encountered in a barn or a basement, not objectionable in any way.

Chemical and Physical Properties of Final Product

The chemical and physical properties of the finished compost varied slightly with retention time. The following values (except for potassium and nitrate) are averages of 20 separate analyses:

Total Kjeldahl nitrogen (% N by weight)	2.21
Total nitrate (% NO_3^- by weight)	<0.01
Total phosphorus (% P_2O_5 by weight)	2.16
Total potassium (% K_2O by weight)	0.27
pH	6–6.5
Bulk density (lb/cu ft)	48.2
Moisture (% by weight)	20–35
Color	Dark brown
Odor	Musty

The "fertilizer value" (nitrogen and phosphorus) of the finished compost is low compared with commercial fertilizers, but is about equal that of cattle manure. More important is the ability of the finished compost to condition the soil to absorb and retain water. The general appearance is that of a rich humus such as peat moss.

The value of the finished compost as a soil conditioner was demonstrated by spreading 12 to 15 lb of compost per sq yd on a private lawn. The soil on which the finished compost was applied was sandy, low in humus, and low in natural fertilizer content. This compost added humus and did not cause any noticeable deleterious effects; the grass (lawn) responded by turning a rich, dark-green color and growing profusely. The added compost also aided soil aeration by preventing the soil from packing. All of the above characteristics have value and indicate that the finished compost used in this case was effective as a soil conditioner.

The moisture of the finished compost depended on retention time in the composter and reflected the degree of stabilization accomplished. The relation of compost temperature to number of curing days has been plotted for compost with moisture contents of 23 and 32 percent (Figure 15).

The temperature of the low-moisture (23%) finished compost decreased to ambient temperature almost immediately after being removed from the composter and placed in open piles. This indicates the completeness the overall process achieved while the compost was in the composter (25% solids reduction). After being removed from the composter, the high-moisture (32%) finished compost maintained its temperature for 5 to 6 days before decreasing to ambient temperature. This also reflected the degree of stabilization (4% solids reduction). These results indicate that the moisture of the finished product reflects the completeness of the overall treatment process and that both volatile-solids destruction and drying vary with retention time.

A sample of the finished compost was cultivated for 1 month under controlled laboratory conditions to determine if viable plant seeds were present. The sample was watered daily with distilled water and left in a warm, lighted area. After 1 month, the sample was examined to determine if seeds, possibly present in the sewage sludge initially, were viable after composting. No seeds germinated; the compost retained water well and did not pack or lump. The odor was musty but not objectionable. This test, although conducted only once, added valuable information about the characteristics of the finished compost.

Particle size of the final product also varied with the retention time because size was determined to some extent by moisture content. Moisture contents of the finished compost (between 20 to 28%) resulted in a fine-textured material similar to sawdust with a bulk density of about 48 lb per cu ft.

The pH level of the end product was consistently between 6.0 and 6.5. This level should pose no problem in handling, final use, or disposal.

The concentration and type of organisms remaining in the finished compost would make it a hygienically safe soil conditioner. Pathogenic organisms initially present and indicator organisms added in the pathogenic study were destroyed in a maximum of 3 days. The excellent destruction of pathogens was probably due to the more or less uniformly high temperature maintained and the thorough mixing of the compost bed. The thermophilic organisms, none of which were pathogenic, should pose no problem at ambient temperatures.

In general, the physical and chemical properties of the finished compost would make it a safe soil conditioner with some "fertilizer value."

Survival of Pathogenic Organisms

Because of the possible uses of the finished compost, a very important phase of this study was the survival of pathogenic organisms through the treatment process. Studies [6-8] of the destruction of pathogens in composted garbage and a combination of sewage sludge and garbage indicate that destruction occurs primarily as a result of two actions: thermal kill by high temperature and the effect of antibiotic action. This study was made to determine the destruction of pathogenic type organisms associated with sewage and sewage sludges. Basically, the organisms chosen were those that simulate actual conditions and that also cause infection when entering the body via the gastrointestinal route. Because *Clostridium* and *Staphylococcus aureus* do not meet these criteria, they were not used. The choice was also based on the anticipated problems of detection in the filter cake and final compost, their possible presence in sewage and sewage sludges, and the various types (bacteria, virus, etc.) that could be present. The four pathogenic-type organisms studied were *Salmonella newport,* a bacterium; *Candida albicans,* a fungus; *Ascaris lumbricoides,* a nematode (metazoan parasite ova); and poliovirus Type I, a virus.

A flow diagram of the sequence of testing and method of microbial analyses is shown (Figure 16). The initial work involved establishing techniques for detecting each of the above organisms in filter cake and the final compost. This caused problems because of the many other organisms present and the development of a proper sampling technique. Although *S. paratyphi* was first studied, the sensitivity of the technique for its detection was not satisfactory and another organism, *S. newport,* was used. In general, much study was made to gain confidence in detecting techniques that were to be used during insertion studies.

Alcaligenes species

The destruction of microorganisms in the composter was significant. Tests, made with nutrient agar incubated at 37 C, indicate that total organisms were reduced from 2.1×10^7 to 1.1×10^3, or 99.99 percent kill. The count of gram negative enteric bacteria, employing MacConkey plates for detection, showed 5.6×10^5 organisms per g in the filter cake and zero organisms in the final compost. The predominant organisms in both the filter cake and final compost were Alcaligenes species. These are nonpathogenic, alkali-producing bacteria associated with the breakdown of proteins in sewage. Interestingly, tests indicated a 50-fold increase in

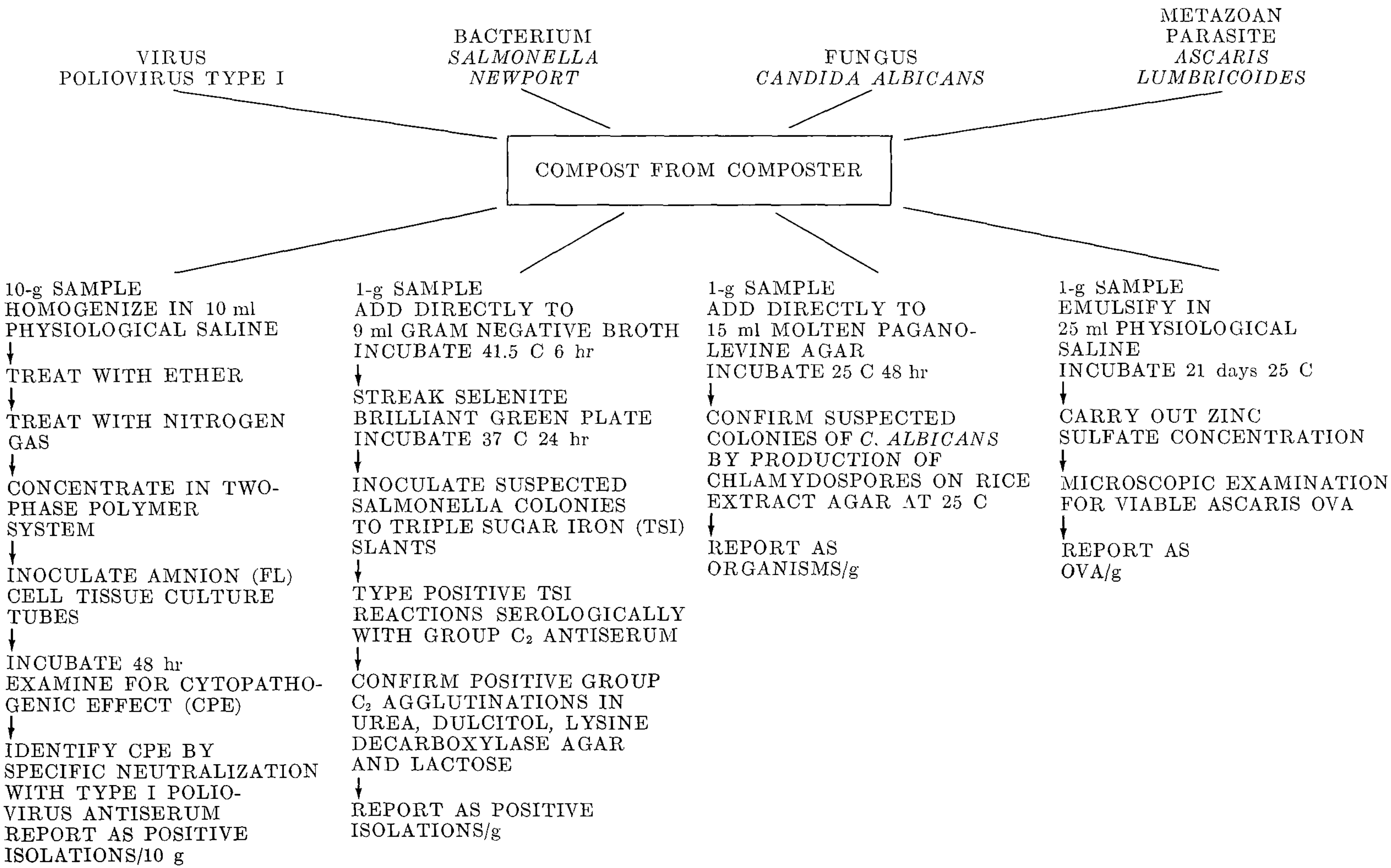

FIGURE 16. Assay for indicator organisms in composted solid human wastes.

thermophilic organisms from 2×10^4 organism per g in the filter cake to 1.5×10^6 organisms per g in the final compost.

Laboratory and insertion tests were made with the use of each of the microorganisms indicated in Figure 16. Aseptic sampling techniques were used throughout these studies of pathogens. The results for each are discussed separately.

Salmonella newport

These pathogenic bacteria are found in sewage. When laboratory tests were made to determine the thermal death point (TDP) (time is a constant and temperature is varied) and the thermal death time (TDT) (temperature is a constant and time is varied) of *S. newport,* the TDT was 30 min at 60 C and the TDP was 65 C in 30 min. These results indicated that *S. newport* is susceptible to kill at temperatures existing during composting treatment (60 C to 140 F). This organism was not isolated in either the filter cake or final compost before inoculation. Insertion studies involved 117 microbial analyses after the compost in the composter (40 ft^3 volume) was inoculated with 2.7×10^{12} organisms. Samples of the compost were removed from the inlet and outlet portions of the composter at given time intervals. One hour after inoculation the tests indicated *S. newport* was present at the inlet zone and after 4 hr, at the outlet. No *S. newport* was found in the inlet or outlet zones 25 hr after inoculation. Sampling continued for 10 days with no further isolation of any organisms, not even coliform,[9–12] on the selective medium or on selenite brilliant green agar.

Candida albicans

These pathogenic yeasts survived well at 37 C in both water and sewage. The selective medium used to isolate this organism was Pagano-Levin medium.[13, 14] Again, no organisms were isolated from the filter cake or final compost before inoculation. The TDP was established at 80 C for 30 min, and the TDT was 60 min at 70 C. This also showed susceptibility to kill at composting temperatures.

Insertion studies employing 2.0×10^9 organisms mixed into the composter feed were tried. One hour after the compost had been inoculated with the microorganism, analysis of samples taken at the composter inlet showed isolation of *C. albicans* too numerous to count. At least one organism per gram was isolated after 28 hr at the outlet from the composter. No further isolation occurred during the next 3 days of sampling involving 30 additional analyses.

Ascaris lumbricoides

These pathogenic nematodes (small worms) are found in the intestines of hogs. The ova used during this study were taken from hog intestines obtained from a local abattoir. After the whole worm was removed from the hog intestines, their uteri were removed, homogenized, placed in a saline solution, and refrigerated for future use.[15] Laboratory tests indicated a TDP of 60 C for 60 min. No tests were made on the TDT.

Insertion studies involving the inoculation of 1.4×10^8 organisms into the composter were performed. The results of these tests showed that viable ova were not present 4 hr after inoculation. Ova were found 1 hr after inoculation at the inlet and up to 76 hr at the outlet of the composter; after 76 hr, ova were not detected. The ova began to disintegrate 24 hr after inoculation; this accounts for their total absence after 76 hr. A total of 110 microbial analyses were made.

Poliovirus Type I

This virus was the most susceptible to high-heat kill; its TDP was 50 C for 30 min, and its TDT was 5 min at 60 C.

The separation technique used to isolate this virus involved a two-phase polymer system to concentrate the samples, followed by inoculation into cultures of FL cells and examination for cytopathogenic effects. The final test consisted of treating suspected samples with anti-poliovirus Type I antiserum and observing the results.

TABLE 1

SOURCES AND QUANTITIES OF SOLIDS TO BE TREATED AT 1-MGD SEWAGE TREATMENT PLANT

Item	Primary treatment	Primary and secondary treatment
Raw waste:		
SS* (mg/liter)	250	250
BOD_5† (mg/liter)	200	200
Primary treatment:		
65 percent SS removal (mg/liter)	160	160
40 percent BOD_5 removal (mg/liter)	80	80
Secondary treatment:		
85 percent removal of BOD_5 from primary effluent (mg/liter)		100
BOD_5 removed, converted to solids (~50 percent) (mg/liter)		50
Total dry solids removed (mg/liter)	160	210
Total dry solids in 1 mgd (lb)	1, 340	1, 750
Total wet solids (~70 percent moisture) in 1 mgd (lb)‡	5, 100	6, 700
Total wet solids (45 lb/cu ft) in 1 mgd (cu ft)	114	149

*Suspended solids.
†Biochemical oxygen demand, 5 day.
‡Figures adjusted for the addition of 15 percent conditioning chemicals on a dry solids basis.

Initial analysis of the sewage sludge and compost revealed no virus of this strain was present. In the insertion studies, 2×10^7 organisms were mixed into the composter feed. All samples taken at the inlet and at the outlet of the composter were negative. This is reasonable since the TDT of the virus is only 5 min at 60 C.

DESIGN CRITERIA

Application of the composting process requires that certain basic criteria be known. In general, the results of this study established these basic design parameters, and these parameters structured the design of a compost process for a primary and secondary sewage treatment plant with a sewage flow of 1 mgd. When the sources and quantities of the sludges to be treated were listed, it was noted that the secondary portion of treatment adds about 30 percent more sludge to be processed (Table 1). Although the test work involved only the combination of primary and secondary sludges, there is no reason to believe that the process will not work just as well on primary sludge alone. Based on the results obtained from the operation of the pilot plant, a calculated retention time of 7 days (actual retention time about 26 days), an air-flow rate of 0.25 scfm per cu ft, and a mixing horsepower of about 0.05 hp per cu ft (based on paddle mixing, which is not necessarily recommended) is suggested.

The size of the equipment required to process the volume of sludges for the 1-mgd plant (Table 1) varies according to the treatment phase (Table 2).

TABLE 2

DESIGN CRITERIA FOR COMPOSTING PLANT HANDLING SOLIDS FROM A 1-MGD SEWAGE TREATMENT PLANT

Item	Primary treatment	Primary and secondary treatment
Composter:		
Volume (cu ft)	800	1, 000
Depth (ft)	3	3
Mixing, using paddles, (hp)	~40	~50
Air required:		
Volume (scfm)	200	250
Pressure (psig)	1	1
Horsepower	~2	~2

In these design criteria, the compost depth is set at 3 ft. Although this parameter was not studied, it was believed that lesser depths would begin to cause increased cooling and greater depths would require increased power for mixing. Future testing should include a study of depth if this type of mixing is used.

The type of mixing should also be studied in future tests. A better method than the type tested could be more effective. Mixing appeared to be a significant parameter in the process efficiency.

The above design does not include the appurtenant facilities required to feed, recycle, mix, and discharge the final product.

The operation of the pilot plant indicated that the entire process could be nearly automated, with a minimum of manual operation required. Temperature and dissolved oxygen probes could be used to control the rate of mixing and air-flow rate. Moisture sensors in the compost bed and feed could be used to control recycle and feed rate, and a bed level control could be used to control the discharge of final product.

The types of equipment for materials handling would necessarily be designed on the basis of volume, consistency, and location requirements of the composter layout.

Conclusions

1. The process was capable of reducing moisture, volume, weight, and solids by an average of 87, 73, 73, and 30 percent, respectively.
2. Continuous mixing and aeration of the compost bed was required to ensure good odor-free treatment.
3. The air requirement for drying was critical and well in excess of the air required to maintain aerobic conditions.
4. Recycling was not only beneficial, but necessary; it facilitated moisture adjustment of the feed and microbial (aerobic thermophilic) seeding.
5. The final compost had a nitrogen and phosphorus content of a little over 2 percent each, expressed as N and P_2O_5; this compost worked well as a soil conditioner and was found to be free of indicator pathogens and viable plant seeds.
6. The study of pathogens indicated that all of the test organisms (*Salmonella newport, Candida albicans, Ascaris ova,* and poliovirus Type I) inserted in the compost were killed in less than 3 days' retention in the composter.
7. The chemicals used had a dramatic effect on the process. Sludge conditioned with lime and ferric chloride produced compost that mixed and handled better than sludge conditioned with polymer.
8. Moisture content of the feed and the compost bed were critical for proper treatment. The optimum moisture content in the compost bed was 25 to 30 percent by weight.

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