Changing Mesophilic Wastewater Sludge Digestion into Thermophilic Operation at Terminal Island Treatment Plant

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ABSTRACT: This paper describes the progress up to June 2000 for thermophilic digestion of wastewater sludge at the Los Angeles, California, Bureau of Sanitation's Terminal Island Treatment Plant. The development of the microorganism culture has followed a course similar to that seen at other successful plants for establishment of a stable, well-balanced thermophilic culture in a large digester, but at an accelerated pace. This study began with rapid heating, increasing the temperature of the 4500 m^3 (1.2 mil. gal) digester to the target temperature of 55 °C at approximately 3 °C/d. A method of feeding to maximize the rate of culture development was used as feeding accelerated to approximately 400 m^3/d (0.1 mgd). An initial rise of acid concentration (primarily acetate) was seen. Within two weeks, acid concentration declined and stabilized, indicating that acidogenic and methanogenic microbial communities came into balance. Coliform data indicate that digester disinfection was stably effective from the middle of April. The salmonella tests done to date satisfy the U.S. Environmental Protection Agency (U.S. EPA) class A specification. Testing with helminth ova and enteric viruses before and after the digester shows satisfaction of class A standard for those organisms. The present combination of low volatile fatty acids and low hydrogen sulfide is good news for odor control. The data show increases in volatile solids destruction and estimated gas production, compared with the previous mesophilic operation; however, large uncertainties have been calculated from the data. As the digester is now operating successfully at the current feed rate, there seems to be no barriers to processing the entire sludge production of the plant. Other results indicate that the U.S. EPA requirements for exceptional quality class A biosolids are likely to be achieved. *Water Environ. Res.,* **74,** 494 (2002).

KEYWORDS: class A biosolids, pathogens, disinfection, thermophilic operation, volatile acids, feed rate, alkalinity, biogas.

Introduction

The Los Angeles, California, Bureau of Sanitation has a long history of involvement with thermophilic digestion. Garber (1954) and Garber et al. (1975) are historically important reports on large-scale operational uses of thermophilic digestion in the United States. Nevertheless, in both of these earlier periods changing economic, demographic, and regulatory conditions led to a return to purely mesophilic processing after only a few years. Now that the bureau is conducting a new project in response to regulations to produce biosolids that meet the class A standard, it is able to do so with considering the biology and chemistry of thermophilic digestion (e.g., Ahring et al., 2001; Andrews and Pearson, 1965; McCarty, 1964).

A review of the literature dating to the classic paper of Fair and Moore (1934) shows that the temperature dependencies reported in both Garber papers were highly anomalous for thermophilic digestion. These results very strongly indicate that the slow heating used by Garber and his colleagues led to development of a culture dominated by thermotolerant mesophilic organisms rather than true thermophiles, as may be inferred from Aitken and Mullenix (1992). Such a culture may not produce class A biosolids under contemporary conditions, because Garber et al. (1975) showed clearly that their culture could not operate at the temperatures of 55 °C or higher that are needed to achieve the required pathogen-kill factors in digesters with continuous drawing and filling (Ahring, 1994; Iranpour and co-workers, 2001a).

Regulations will soon take effect requiring the bureau's digested sludge to meet the class A standard. The Terminal Island Treatment Plant (TITP), located in San Pedro, California, is the smaller of the two Los Angeles plants that perform solids handling. The present study was undertaken to test the ability of one or more thermophilic digestion processes to meet the city's needs for disinfection effectiveness, reliability, and tolerable costs. A diverse task force, composed of personnel from TITP; the Applied Research Environmental Monitoring Division and Management Group of the Los Angeles, California, Bureau of Sanitation; and consultants from the University of California at Los Angeles (UCLA) and Technical University of Denmark, Lyngby, was assembled for the project (Iranpour and co-workers, 2001b).

Because the digesters at TITP are large (approximately 4500 m^3 [1.2 mil. gal]), transporting enough seed culture from an established thermophilic digester would have cost too much. Hence, the tests have been conducted with attention to heating and feeding methods that maximize the rate of culture development from the tiny populations of dormant thermophilic organisms usually present at ambient temperatures in biological wastes. Specifically, the objectives of this study were to

- As quickly as possible establish a balanced digestion culture (indicated by a total volatile fatty acid [VFA] concentration of less than 1000 mg/L), using mesophilically digested sludge as the initial source of thermophilic organisms, and small quantities of raw sludge as the food source;
- Demonstrate disinfection to meet class A standard (alternatives 1 or 3 of 40 CFR Part 503 [U.S. EPA, 1993]) once the target temperature and a balanced culture were established;
- Achieve volatile solids (VS) destruction and gas production comparable to or greater than those currently obtained from mesophilic digestion, once the target temperature and a balanced culture were established;
- Determine whether the culture activity in the digester used in

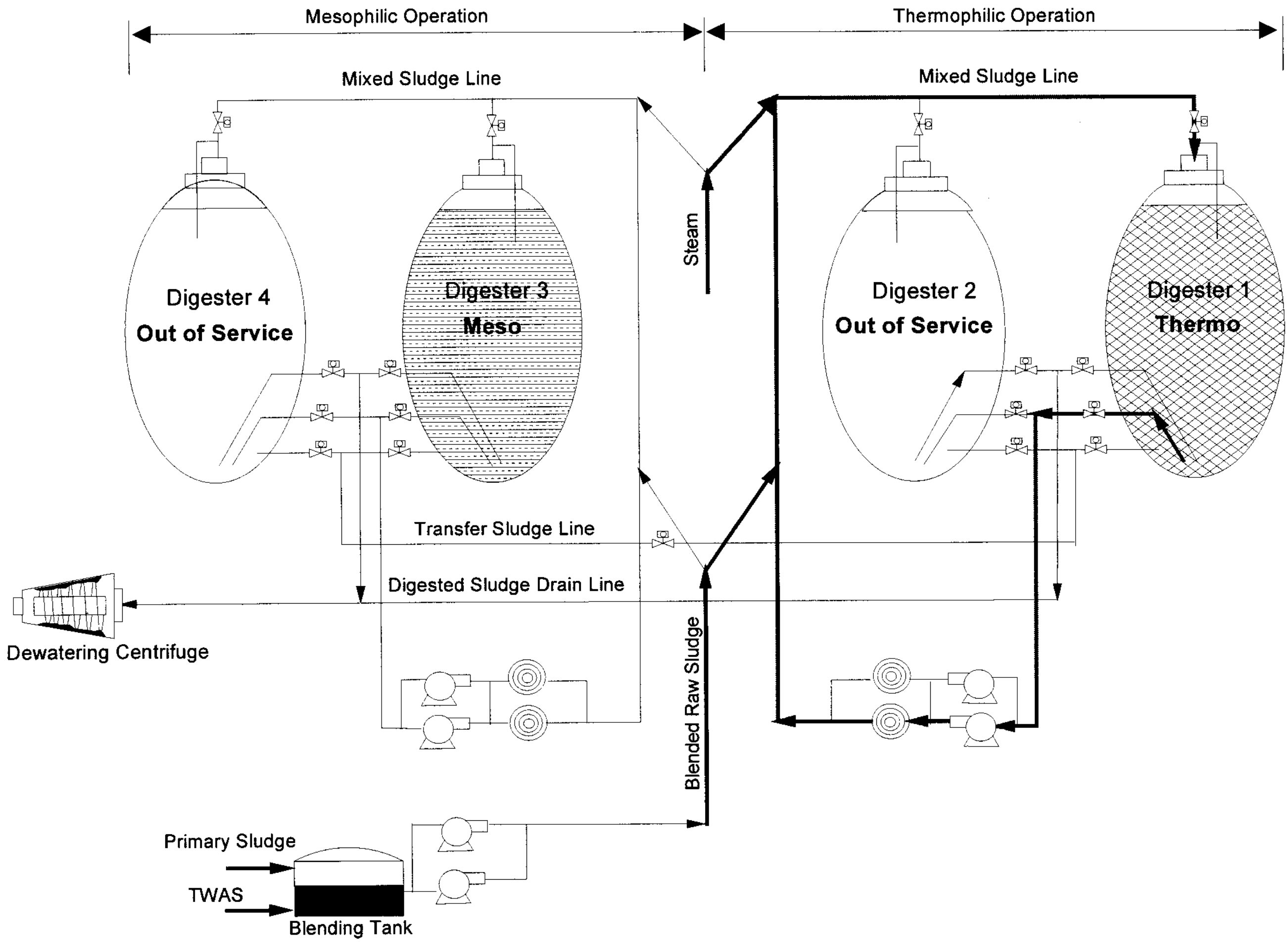

Figure 1—One-stage thermophilic operations at TITP (February to June, 2000).

the study could be raised high enough to process the plant's entire production of approximately 450 m^3/d (0.12 mgd) of thickened raw sludge while maintaining a balanced culture, class A disinfection, and satisfactory volatile solids destruction and gas production;

- Determine whether the initially chosen plan of rapid heating and gradual increase in feeding would achieve the first four objectives;
- Monitor the chemical and physical state of the digester in sufficient detail to detect any difficulties that might arise and take suitable corrective action; and
- Develop preliminary economic models and analyses.

Legal Background

The statement of the CFR 40, Part 503 class A pathogen standard constitutes Section 32 of the regulation (U.S. EPA, 1993). The primary concern is to reduce the bacterial density to a safe level. Therefore, all alternatives for meeting the standard specify that either the concentration of fecal coliform never exceeds 1000 most probable number (MPN)/g of total dry solids or the concentration of *Salmonella* never exceeds 3 MPN/4 g of total dry solids. As the kill rate for pathogenic organisms increases exponentially with temperature at greater than 50 °C, alternative 1 of the standard states that sludge with less than 7% solids is expected to be free of other pathogens if it is thermophilically digested for at least a period, in days

$$D = 50\ 070\ 000/10^{0.14T} \tag{1}$$

where T is the temperature (°C). If T is high enough such that D in eq 1 is shorter than 30 minutes, then 30 minutes must be used. Sludge that has not been treated this way still meets the standard if it satisfies the bacteriological requirement and either has been subjected to any of a variety of other treatments (alternative 2, 5, or 6), helminth ova and enteric viruses are undetectable before or after treatment (alternative 3), or helminth ova and enteric viruses are undetectable at the last point of plant control (alternative 4).

Vector attraction is covered in Section 33 of the regulation (U.S. EPA, 1993). It may be satisfied by meeting any one of eight conditions, one being a volatile solids reduction of at least 38%. Section 13 and related sections specify standards for metals content (U.S. EPA, 1993, 1995). Biosolids satisfying the class A standard (section 503.32), the vector attraction regulation (section 503.33), and the lowest metals content standard (section 503.13) are said to have exceptional quality (U.S. EPA, 1994a).

Although the general requirements of federal standards are satisfied by meeting either the fecal coliform or the salmonella limit, recently passed ordinances in some California counties require both to be met by biosolids supplied as soil amendments for farms. There are also many legal cases and controversies over the use of biosolids in many parts of the United States and Europe (Evans, 2001; Iranpour and co-workers, 2001c; Matthews, 1997;

Table 1—Information on laboratory analysis for selected parameters.

Parameter	Method	Instrumentation	Sampling frequency
Environmental Monitoring Division, Hyperion Treatment Plant, Playa Del Rey, California			
Fecal coliform	Multiple tube fermentation technique, SM 9221 E.2[a]		4 to 5 days per week
Methane	U.S. EPA Method 18[b]	Gas chromatograph	4 to 5 days per week
Carbon dioxide	U.S. EPA Method 18[b]	Gas chromatograph	4 to 5 days per week
Environmental Monitoring Division, Terminal Island Treatment Plant, San Pedro, California			
Alkalinity	Titration, SM 2320 B[a]	pH meter	4 to 7 days per week
VFA (total)	Distillation and titration, SM 5560 C[a]	Centrifuge, distillation assembly	4 to 7 days per week
Total solids	Gravimetric, SM 2540 B[a]	Balance, oven	4 to 7 days per week
Volatile solids	Gravimetric, SM 2540 E[a]	Balance, furnace	4 to 7 days per week
pH	Electrometric, SM 4500-H^+ B[a]	pH meter	4 to 7 days per week
Hydrogen sulfide	Colorimetric tube[c]	Drager analyzer	4 to 7 days per week
Environmental Engineering Laboratory—University of California, Los Angeles, California			
VFA (individual)	VFA levels as free acid	Gas chromatograph with flame ionization detector	Three times per week
BioVir Laboratories, Benicia, California			
Salmonella	Multiple tube enrichment technique, SM 9260 D.1[a]		Three times
Helminth ova	U.S. EPA 600 (samples composited in laboratory)[d]		Every 8 hours for 4 weeks
Enteric virus	ASTM D 4994-89 (samples composited in laboratory)[e]		Every 8 hours for 2 weeks

[a] *Standard Methods* (APHA et al., 1992).
[b] Hyperion Treatment Plant standard operation procedure based on U.S. EPA Method 18 (40 CFR Pt. 60, App. A, Meth 18) for analysis of fixed gases in air and gaseous samples by gas chromatography (U.S. EPA, 1994b).
[c] Terminal Island Treatment Plant standard operating procedure for determination of hydrogen sulfide in digester gas by Drager chip measurement system analyzer (Drager Safety, Inc., Pittsburgh, Pennsylvania) (SCAQMD approved).
[d] Yanko (1987).
[e] ASTM (1992).

O'Dette, 1993) that present many challenges for wastewater treatment plants in the future.

Methods and Design Issues

Experimental Setup. The TITP has a capacity of approximately 0.1×10^6 m^3/d (30 mgd) of wastewater. It receives some domestic wastewater, but approximately 10% of the influent is seawater and historically 40 to 60% has been industrial, including irregularly timed discharges of wastewater from metal plating, fish canning, the Long Beach Naval Shipyard, several oil refineries, and chemical plants. Thus, the plant always has had high sulfide and salinity concentrations in its influent, frequent high heavy metals and oil and grease concentrations, and highly variable pH and biochemical oxygen demand, suspended solids, and ammonia concentrations.

Figure 1 shows the existing digesters at TITP. Only one digester (digester 1) was used for thermophilic operation. As noted previously, in operation each digester holds approximately 4500 m^3 (1.2 mil. gal) of sludge. Filling with mesophilically digested sludge and heating the initial charge began on February 15, 2000, at an average temperature rise of 3 °C/d. The planned temperature of 55 °C (130 °F) was reached by February 21 and the first very small feeding of 6.1 m^3 (1600 gal) was done on February 23. To avoid permit violations, the mesophilic operation was continued at TITP using digester 3. Digesters 2 and, later, 4 were removed from service to be cleaned for use if additional thermophilic digestion was needed, or for storage in two-phase digestion.

This figure shows important operational components. Mixing is accomplished by a combination of recirculation and gas recycling from the headspace of a digester to injection pipes near its bottom. However, each digester is so large that the characteristic time to achieve full mixing using both gas recycling and recirculation is at least one-half a day. Hence, feeding, which occurs at the top of a digester, occurs simultaneously with withdrawal, done at the bottom, most likely without contamination of the outflow by the inflow. As the outflow was sampled for coliforms and pathogens at times that varied from coinciding with feeding to several hours afterward, the outflow was expected to show low pathogen levels; sampling results confirm this.

Laboratory Procedures. Table 1 summarizes the methods, instrumentation, and sampling frequencies for analysis of the various components of the samples. Monitored parameters were analyzed by four different laboratories: Environmental Monitoring Division (EMD) laboratory, Hyperion Treatment Plant, Playa del Rey, California; EMD laboratory (TITP); environmental engineering laboratory, UCLA; and BioVir Laboratories, Benicia, California.

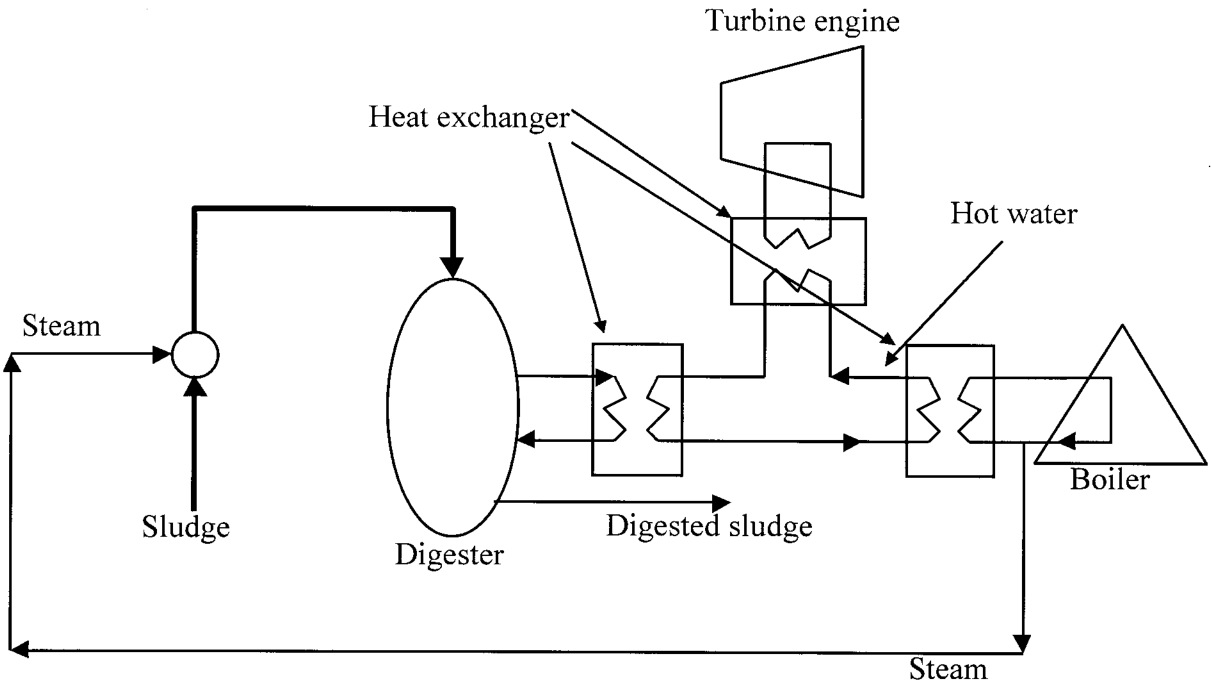

Figure 2—Heating scheme for thermophilic operations.

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500	0600
Mode	Feed		No feed & no withdraw						Feed		No feed & no withdraw						**Withdraw** **Mon to Thurs:** Lower digester level to 17.4m **Fri:** Lower digester level to 15.8 m for weekend feed **Sat & Sun:** No withdraw							
Flow rate	0.57 m³/min								0.57 m³/min								Depends on centrifuge status							

(a) 136 m³/day (36,000 gpd), 3/14 - 19

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500	0600
Mode	Feed		No feed & no withdraw						Feed		No feed & no withdraw						Feed		**Withdraw** **Mon to Thurs:** Lower digester level to 17.4 m **Fri:** Lower digester level to 15.8m for weekend feed **Sat & Sun:** No withdraw					
Flow rate	0.49 m³/min								0.49 m³/min								0.49 m³/min		Depends on centrifuge status					

(b) 177 m³/day (46800 gpd), 3/20 - 27

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500	0600
Mode	Feed								Feed								Feed							
	No withdraw																**Withdraw** **Mon to Thurs:** Lower digester level to 17.1 m **Fri:** Lower digester level to 15.8m for weekend feed **Sat & Sun:** no withdraw							
Flow rate	0.45 m³/min								0.45 m³/min								0.45 m³/min							

(c) 245 m³/day (64,800 gpd), 3/28 - 4/25

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500	0600
Mode	Feed								Feed								Feed							
	Withdraw			No withdraw													**Withdraw** **Mon to Thurs:** Lower digester level to 17.1 m **Fri:** Lower digester level to 15.8 m for weekend feed **Sat & Sun:** no withdraw							
Flow rate	0.57 m³/min								0.57 m³/min								0.57 m³/min							

(d) 307 m³/day (81,000 gpd), 4/26 - 5/9

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500	0600
Mode	Feed								Feed								Feed							
	Withdraw				No feed & No withdraw												**Withdraw** **Mon . to Fri.:** Lower digester level to 16.8 m **Sat. morn** : Lower digester level to 15.8 m for **Sat. & Sun.:** No withdraw							
Flow rate	0.53 m³/min								0.53 m³/min								0.53 m³/min							

(e) 382 m³/day (100,800 gpd), 5/9 - present

Figure 3—Plans for withdrawal and feed ratio (February to June, 2000).

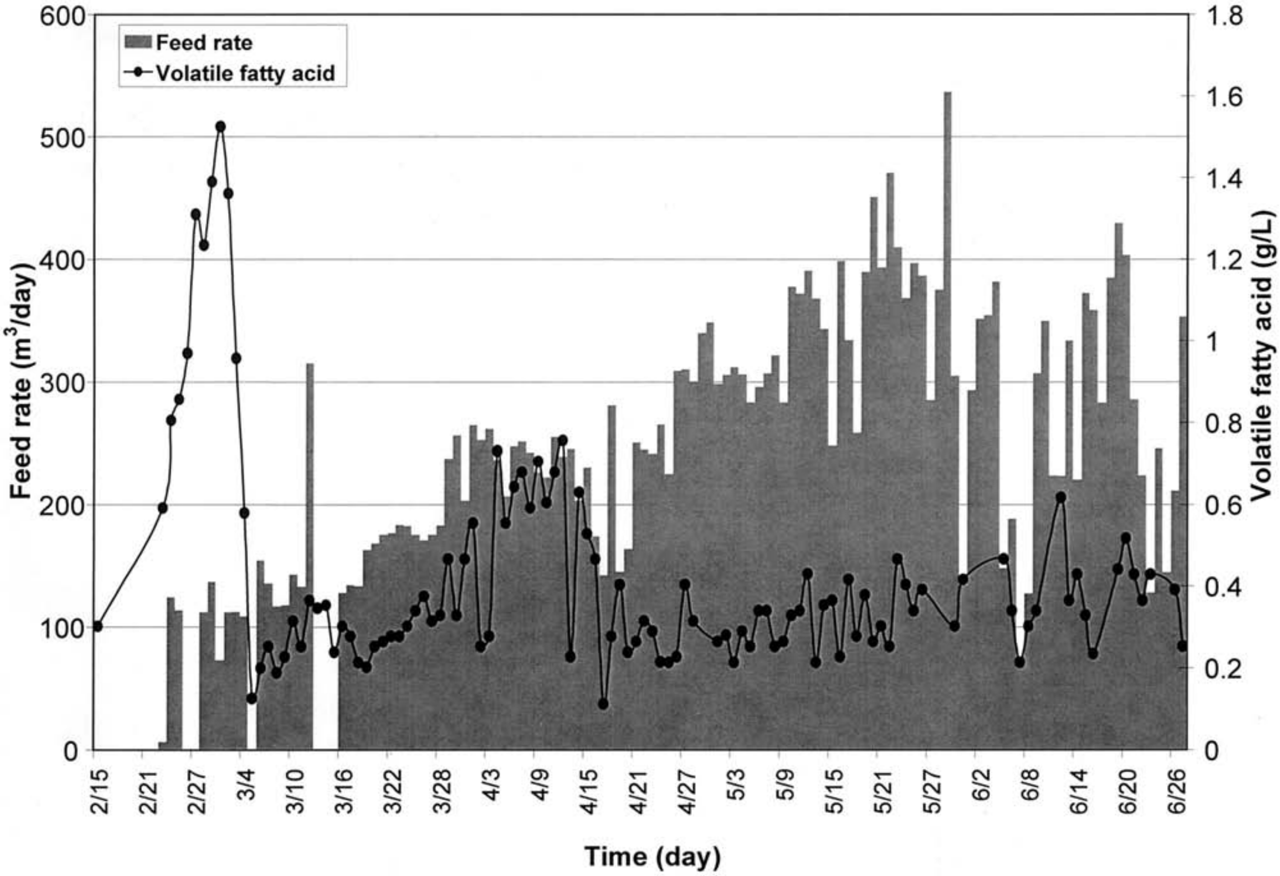

Figure 4—Time history of total volatile fatty acid concentrations and feed rates.

Heating Scheme. For an optimum thermophilic operation, the sludge inside the digester is to be maintained at an optimum near-constant temperature. Initially, the sludge must be heated from approximately the ambient temperature; additional heat is necessary later to counteract heat losses to the surroundings.

Figure 2 shows the sludge-heating scheme used for the thermophilic operation at TITP. The sludge is heated by two different sources. One is steam, which is added directly to the sludge before it goes into the digester. The other source is a heat exchanger, where heat from hot water is transferred to the sludge during recirculation of the digester contents. The hot water supply to the sludge–hot water heat exchanger can be heated through any combination of boiler steam or heat generated by turbine engines. The turbine engines can use digester or natural gas as fuel and are used for power generation. The system allows controlling the amount of heat added by direct injection of steam, by varying the amount of digester sludge that circulates through the digester's heat exchanger, or by changing the amount of heat being transferred to the hot water. These heating options provide flexibility in compensating for variations in the heat losses to the environment and the initial sludge temperature.

Operational Issues. During the startup and stabilization phase of the thermophilic operation several problems were identified in the following categories:

- Heating—The boiler is old, somewhat inefficient, close to its maximum heat generating capacity, and has no reliable backup system. The boiler was sometimes turned off for a few days, usually during weekends. If the boiler fails to maintain a high enough steam pressure, sludge flows into the steam lines.
- Sampling—Samples were sometimes taken without flushing the sampling line, resulting in an unrepresentative sample.
- Mixing—On some occasions the gas compressor system malfunctioned, resulting in loss of gas mixing in the digester.
- Wasted gas—On several occasions the high-pressure gas holder tank was full when the boiler and the gas engines were inoperative, necessitating releasing and burning the digester gas produced.
- Measuring equipment— An old magnetic sludge flow meter that was used may have been unreliable. Two new gas flow meters were installed in an effort to determine the separate flows from the mesophilic and thermophilic digesters, but operational problems arose during measurements.

Feeding History. Five feeding plans had been used by late June 2000. The first plan, in effect from late February to March 19 (Figure 3a), shows that there were to be two feeding periods a day, one from 0700 to 0900, and the other from 1500 to 1700, each with a feed rate of 0.57 m^3 /min (150 gpm). Withdrawal was to be done from 2300 of one day to 0700 of the next. However, this plan was not strictly followed, because there were many days between February 23 and March 14 on which it was decided to feed less than the required 136 m^3 (3.6×10^4 gal), and on some days there was no feeding to allow the culture time to adapt. After March 14, the full rate of 136 m^3/d was scheduled for every day.

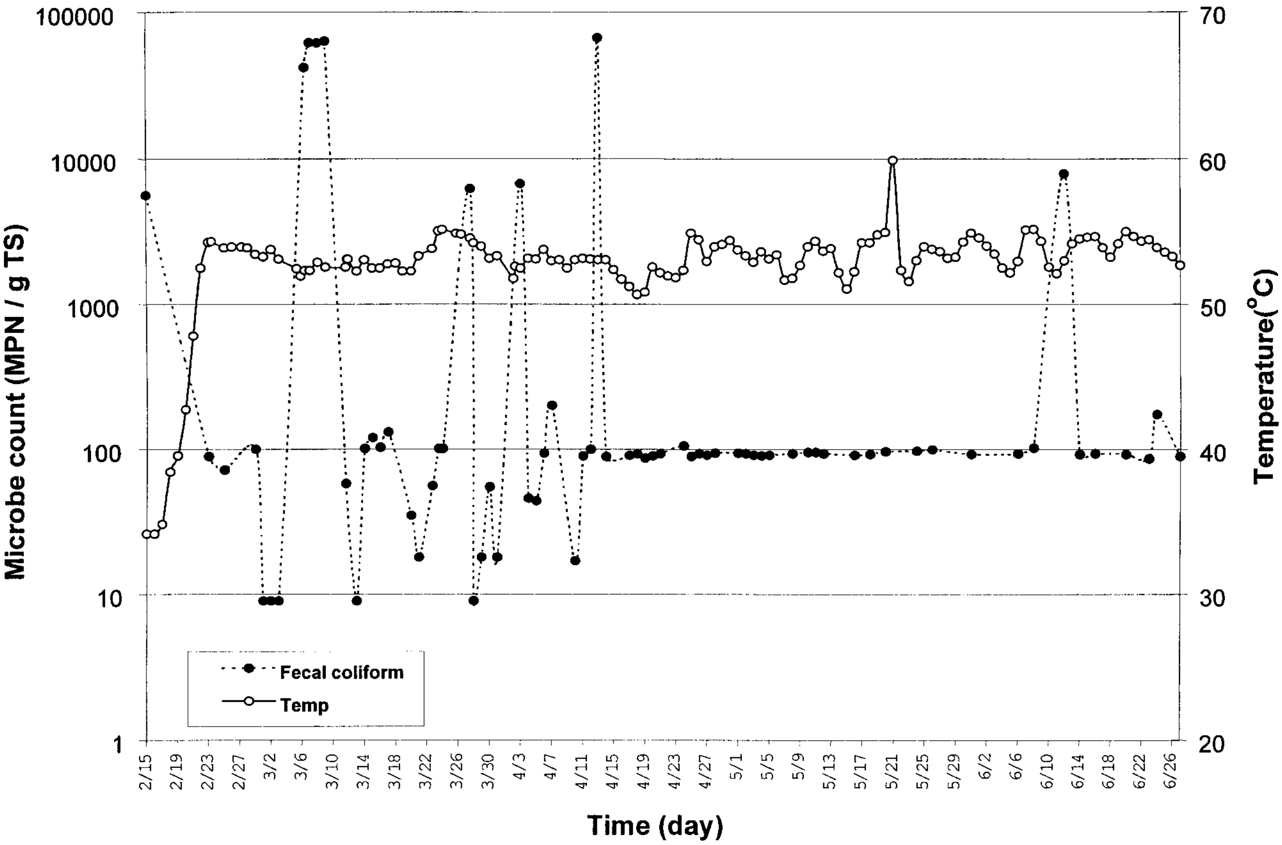

Figure 5—Time history of fecal coliform densities and temperatures.

The second feeding plan was in effect from March 20 to March 27 and is shown in Figure 3b. The feed rate was reduced to 0.49 m^3/min (130 gpm), but a third feeding period was added from 2300 of one day to 0100 of the next, so that the total fed was 177 m^3/d (4.68×10^4 gpd). The withdrawal period was reduced to cover the period from 0100 to 0700. The third feeding plan, in effect from March 28 to April 25, reduced the feed rate to 0.45 m^3/min (120 gpm) and extended each feeding session to three hours, for a total of 245 m^3/d (6.48×10^4 gpd) (Figure 3c). The withdrawal period overlapped the third feeding period, running from 2300 to 0700. The fourth feeding plan, in effect from April 26 to May 9, increased the feed rate to 0.57 m^3/min (150 gpm) and maintained each feeding period at three hours, for a total of 307 m^3/d (8.1×10^4 gpd) (Figure 3d). The withdrawal period overlapped not only the third feeding period but the following day's first period, running from 2300 to 1000. The fifth feeding plan, in effect from May 9 onward, increased the daily feed to 381 m^3/d (1.008×10^5 gpd). This was done by extending the feeding periods to four hours each, changing the flow to 0.53 m^3/min (140 gpm), and extending the withdrawal period to run from 2300 to 1300 (Figure 3e).

The feeding plans were established to allow the TITP operations staff to incorporate feeding the experiment among their many other activities. The succession of plans was designed to increase the amount fed as the digestion capacity of the culture increased (consistent with the pumping capacity of the equipment), equalizing the work load among the shifts and promoting temperature equalization, mixing, and disinfection by providing as long a delay as possible between feeding and drawing. Transitions were made between plans when it was believed that digestion capacity had increased enough that the additional food would provide additional culture development without a process upset.

Because the effort to maintain complete mixing with the recirculation system made the hydraulic retention time and solids retention time the same, dividing the digester capacity of 4500 m^3 (1.2 mil. gal) by the feed rate for each plan gives the digestion time that would result if the plan were maintained for a prolonged period. However, as indicated previously, the second and fourth plans were only in effect for short periods, so that computing the average digestion times during these periods would be more complicated than a simple division and has not been attempted. Furthermore, as shown in Figure 4, the actual feeding rate on a given day often varied from the target rate in whatever plan was in effect at the time (Figure 3). Hence, the actual retention times declined gradually from 30 days or more at the start of the experiment to 12 to 15 days while the fifth plan was used.

Table 2—*Salmonella* concentrations.

Test date	Density (MPN/4 g TS)
4/10	<0.3
4/12	<0.3
6/12	<0.1

Table 3—Helminth ova and enteric virus concentrations.

Parameter	Sampling dates	Sample location	No. samples	Density
Helminth ova (ovum/4 g TS)	1/10/01–2/8/01	in	79	<1
		out	83	<1
Enteric virus (pfu/4 g TS)	1/24/01–2/8/01	in	41	8
		out	43	<1

Results and Discussion

Culture Development. Figure 4 is a plot of the total acid concentration as a function of time, along with the actual feeding history. This figure shows that the development of the culture followed a course similar to that seen at other plants, with an early rise of acid concentration as the acidogen activity initially exceeded the activity of the methanogens, and a later decline and approximate stabilization of the acid concentration as the activities of the microbial communities came into balance. It is also evident that the actual feeding history was more variable than depicted in the feeding plans of Figure 3, with enhanced variation after early May.

The most important information provided in Figure 4 is the speed at which balance was achieved. The period of high acid concentration lasted fewer than two weeks. This clearly is due at least in part to the careful feeding schedule, which started with a relatively low feeding rate and interrupted feeding during the period of imbalance. It is also likely that the initial digester load of mesophilically digested sludge contained significant numbers of dormant thermophilic microbes and, hence, was favorable for development of the needed culture.

As the feeding rate was further increased, the acid concentration rose irregularly in late March and early April, but declined again in late April and early May. A slower, smaller, and more irregular rise occurred from late May through most of June. These are encouraging results, suggesting that the system will be able to accommodate any additional small increases in the feed rate resulting from changing plant loads.

Microbe and Pathogen Reduction. Figure 5 shows the fecal coliform (plotted on a logarithmic scale to accommodate fluctuations over several orders of magnitude) concentration as a function of time. The temperature data show that the temperature was maintained at approximately 55 °C since several days after the beginning of the experiment, with no deviations large enough to interfere with culture development. Although these parameters are much less well correlated than the correspondence of pH with alkalinity and feedings, the excursions to high coliform levels in early March and early April begin at the time of lowest temperature and are consistent with the usually assumed exponential dependence of kill rate on temperature. However, the rise in temperature near the end of March is not accompanied by a rapid further decrease in coliform concentration, but is followed, with a lag, by a rise in microbe count to more than the class A standard of 1000 MPN/g total solids. Another peak occurs during mid-April, just before a significant decrease in temperature, and then, except for one high value in mid-June that seems to be either erroneous or the result of a transient condition, the count stays strikingly constant through June, during further wide temperature swings. Also, the coliform counts are not correlated with the feeding history shown in Figure 4. Hence, the available data do not seem to explain fully the observed fluctuations in coliform count.

It is possible that some of the earlier results were distorted by regrowth in the pipe from which the samples were taken, because sampling was done by opening a valve that was not directly attached to the digester. The sampling procedure was revised in April to require letting an adequate quantity of sludge runout from the valve before the sample is collected, to guarantee that the sample consists of material immediately removed from the digester. Because the disinfection value of thermophilic operation is the primary reason for this project, the almost perfect stability of the coliform count at one-tenth of the class A limit over approximately ten weeks is also highly encouraging. This is especially true considering the temperature swings, from which the experience of previous months would have predicted a greater effect. The swings are attributed to the difficulties with the heat supply noted previously; better control of the temperature is anticipated for the future.

Table 2 shows the digester's effectiveness in removing salmo-

Table 4—Metal pollutant concentrations for exceptional quality biosolids (mg/kg dry solids).

	U.S. EPA 40 CFR Part 503.13			
Source metal	Ceiling values (Table 1)	Monthly averages (Table 3)	TITP thermophilic monthly averages	TITP mesophilic monthly averages
As	75	41	11.5	9.1
Cd	85	39	3.2	4.23
Cu	4300	1500	265	264
Pb	840	300	59	55.6
Hg	57	17	3	2.16
Mo	75	Not applicable	25	25.1
Ni	420	420	46.5	36.2
Se	100	100	58	62.9
Zn	7500	2800	964	844

Table 5—Comparison of solids destruction (mesophilic and thermophilic).

Parameters	Blended sludge (%) (average ± standard deviations)	Digested biosolids (%) (average ± standard deviations)	
		Mesophilic	Thermophilic
Total solids (%)	3.6 ± 0.3	2.3 ± 0.16	2.1 ± 0.14
Volatile solids (% TS)	76 ± 2.4	61 ± 0.9	59 ± 1.1
Total solids destruction	Not applicable	36 ± 9	42 ± 9
Volatile solids destruction	Not applicable	49 ± 9	55 ± 10
Increase in total solids destruction	Not applicable	Not applicable	17 ± 25
Increase in volatile solids destruction	Not applicable	Not applicable	12 ± 20
Expected increase in gas production	Not applicable	Not applicable	20 ± 32

nella during the testing period. Table 3 shows results for removal of enteric viruses and helminth ova during a period that extended beyond the end of the primary digestion study reported here. The salmonella test results showed undetectable densities, verifying compliance with the general requirement of 40 CFR Part 503 for all of the alternatives. The requirement for the other pathogens to be undetectable is also satisfied.

Exceptional Quality. Table 4 lists the results of analyses conducted on the thermophilically digested sludge in March and April for the metal pollutants specified in Part 503.13 of the U.S. EPA standard (U.S. EPA, 1993). The first two columns include the legal limits from Tables 1 and 3 of the standard for these pollutants in exceptional quality biosolids. The third and fourth columns give averages for mesophilically digested sludge at TITP during 1999 and the results for the thermophilic operations. The results from the thermophilic samples are generally consistent with the 1999 averages and are below all the U.S. EPA limits. As shown in Table 5, both processes exceed the minimum 38% volatile solids destruction to meet the vector attraction standard, so these biosolids have exceptional quality.

Chemistry and Culture Health. Another view of the chemistry of the digester is provided by Figure 6, which compares pH to

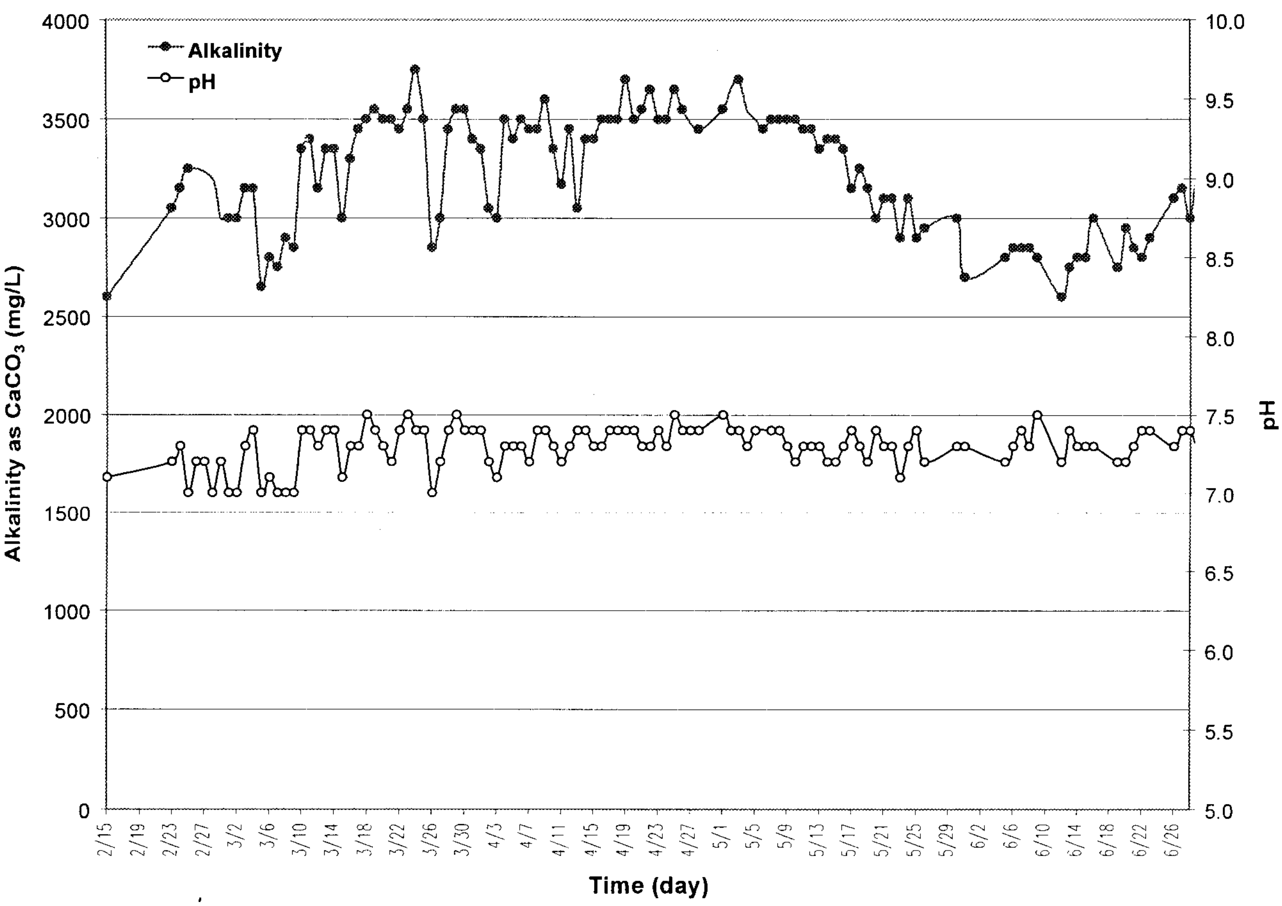

Figure 6—Time history of alkalinity concentrations and pHs.

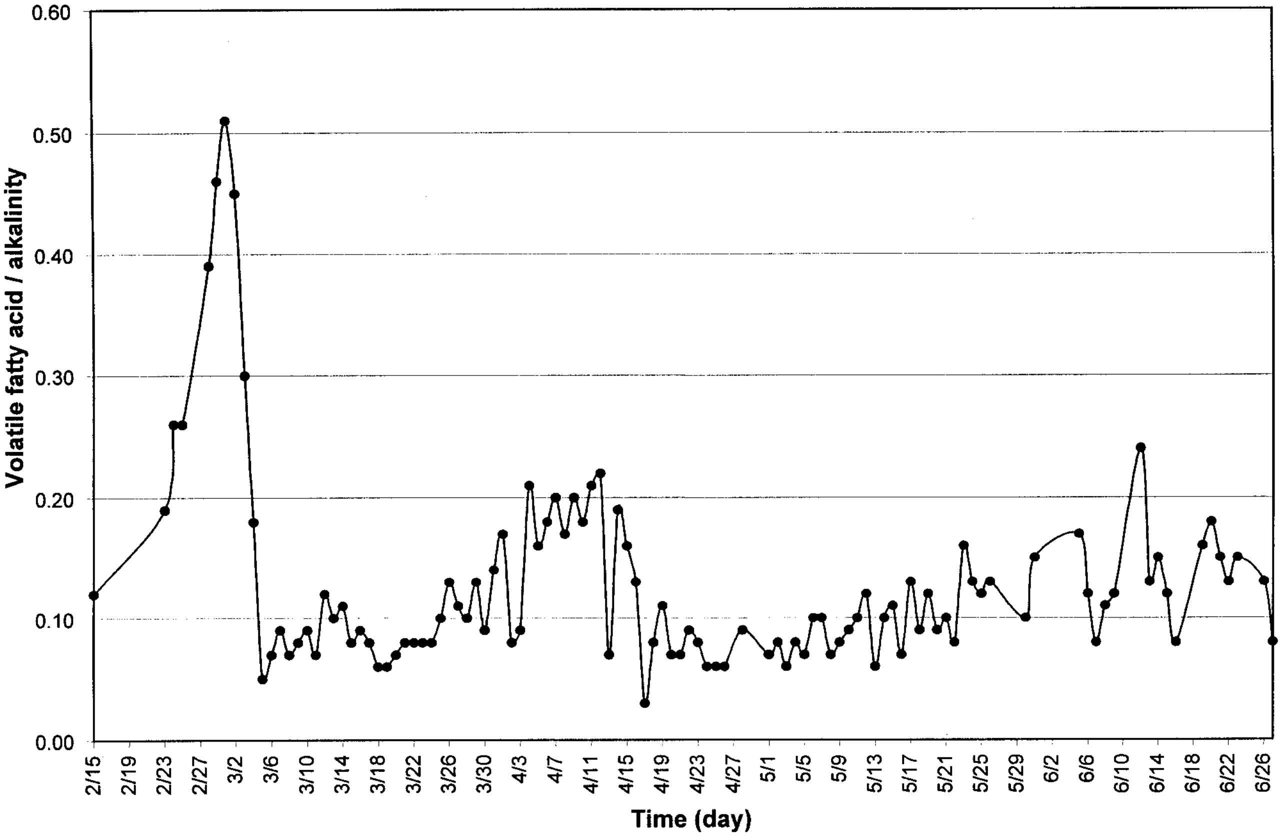

Figure 7—Time history of volatile fatty acid/alkalinity ratios.

alkalinity. The fluctuations in pH and alkalinity are well correlated, despite the small magnitude of pH variations. In addition, the pH remained nearly stable at very slightly alkaline values during the entire period of the study, despite the wide variations of acid concentration shown in Figure 4. On the other hand, the alkalinity began to decline when the feed rate was increased to 380 m^3/d (0.1 mgd) and reached a minimum near the equivalent of 2500 mg/L calcium carbonate before increasing to more than 3000 mg/L in late June.

Corresponding changes in pH and alkalinity would be expected from the rapid increase of acid production when the acidogens receive an increased supply of food, and the corresponding consumption of alkalinity that neutralizes much, but not all, of the additional acid. Later, the alkalinity is restored and the pH increases slightly as the methanogens consume the additional acid. Because these fluctuations were small until early June, they show that the digester culture was adapting successfully to the changes in food supply during this period.

Comparing Figures 4 and 6 suggests, as shown explicitly in Figure 7, that even at the peak of the acid concentration it was no more than half of the alkalinity. Further, since the large decrease of the acid concentration in early March, the acid/alkalinity ratio has been in the range of 0.10 to 0.25, as is typical for healthy digester cultures in both the thermophilic and mesophilic temperature ranges (Pohland and Bloodgood, 1963). Figure 7 also confirms that, because the alkalinity was nearly stable until the middle of May, the changes in the ratio during this period primarily were due to the changes in the acid concentration and that the more recent variation in the alkalinity temporarily increased the ratio from approximately 0.08 to approximately 0.15, before the most recent decline.

Additional insight to the development of the digester culture is provided by Figure 8, which shows the concentrations of individual VFAs. The early peak was predominantly acetate, as expected under a condition of imbalance between the methanogens and the acidogens and acetogens. On the other hand, the peak in early April clearly results from a temporary excess of propionate. Propionate degradation is now known to occur by a different and slower pathway than the cleavage of acetate into methane and carbon dioxide, explaining why a propionate buildup has long been recognized as an unfavorable development indicative of the potential for souring (Pohland and Bloodgood, 1963). However, the microorganism population was able to adapt, perhaps aided by the brief reduction of the feeding rate on April 2 and 3.

Figure 9 shows that the relative proportions of the principal gases produced by the fermentation have fluctuated only modestly since the acid concentration decreased in the early days of March and have stayed in concentration ranges of 60 to 65% methane and 35 to 40% carbon dioxide that are expected for the rates of acetate cleavage and carbon dioxide reduction typical in biogas fermentation systems (Boone, 1989; Stronach et al., 1986). On the other hand, the first few points provide the most direct observation in these data that methanogen activity was low when the acid concentration was high, because this was the only time when the methane concentration was less than 60% and the carbon dioxide concentration was correspondingly higher than at any later time. The slight shifts in methane/carbon dioxide ratios since the middle of March are consistent with the simultaneous variations in acid

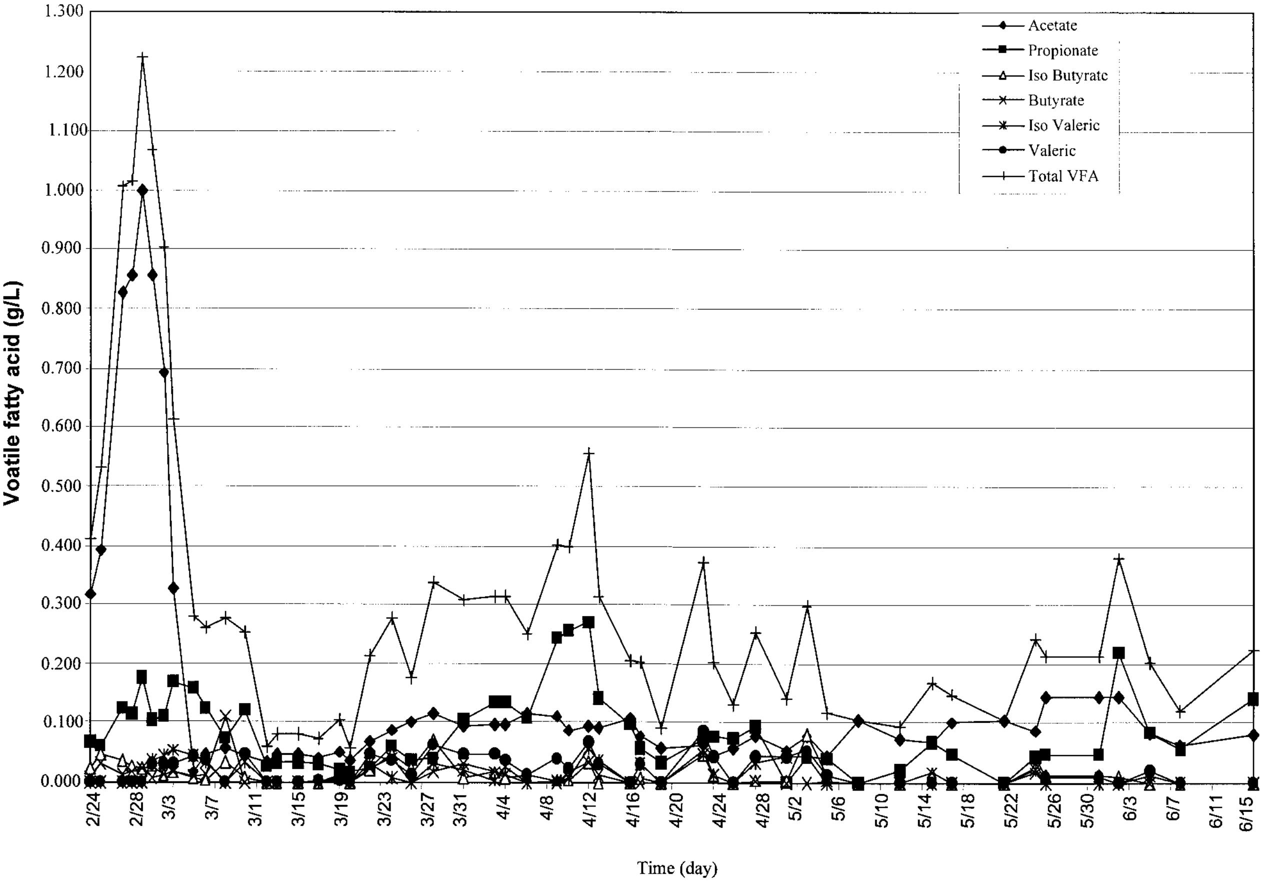

Figure 8—Time history of individual volatile fatty acids.

and alkalinity concentrations seen in Figures 4 and 6 through 8. All of this implies temporary variations in degradation effectiveness with increasing feed rates, and adjustments by the culture that compensate to a large degree for the changing feed.

Figure 10 shows the time history of the hydrogen sulfide concentration of the gas collected from the digester. The pH values in the figure show that the hydrogen sulfide concentration is not well correlated with pH. However, the results suggest sulfate reduction became less complete as the flowrate increased. In particular, this interpretation is consistent with the especially low hydrogen sulfide concentrations in April and May (after the transient spike at the beginning of April). These months were the period of greatest absolute increases in the feed rate, as seen in Figure 4.

Solids Destruction. Data on solids destruction for the simultaneous mesophilic and thermophilic processes were collected during the spring of 2000. The sludge going into each digester came from a common source, assuring that it had the same initial composition of 70% secondary and 30% primary sludges. The output from each digester changed only slightly from one day to the next, but the quality of the incoming sludge was much more variable. For example, each month the total solids in the daily samples varied from approximately 2% or less (typically, the minimum was approximately 1.5% and once it was as low as 1.1%) up to more than 4.75% (four of the six months had peaks greater than 5.5%). Hence, uncritical comparison of daily values would lead to the conclusion that on some days 70% of the total solids are destroyed and on other days solids are created in the digester, both of which are absurd. Thus, the only way to get meaningful results is to take into account solids retention in the digester.

Table 5 shows the data on total and volatile solids entering and exiting the digesters. The table also shows the percent of total and volatile solids destruction through the digesters. The values in the table are based on monthly averages collected during the period of the study. Monthly averages were used because the retention time of each digester was never less than approximately two weeks, and each digester was well mixed on this time scale so that it averaged out daily fluctuations in the input. Using these averages and propagating the errors according to conventional methods (Bevington, 1969) showed that although the relative standard deviations in the total and volatile solids data are modest, the subtractions needed to compute the destruction rates and the changes in the destruction rates greatly amplify the uncertainties of the derived quantities. The retention time of each digester changed during the study as differing proportions of the plant's sludge production were sent for thermophilic and mesophilic digestion. So, using monthly averages is only an approximation to the effect of the digesters, but it does not seem likely that a more elaborate analysis would change the conclusions that the calculated advantage of using thermophilic digestion is not statistically significant, and the present data do not provide a reliable estimate of the change in the gas production that should be expected from thermophilic digestion.

Economic Analysis. A cost analysis was prepared using ideal conditions and a linear model (Iranpour and co-workers, 2001) as

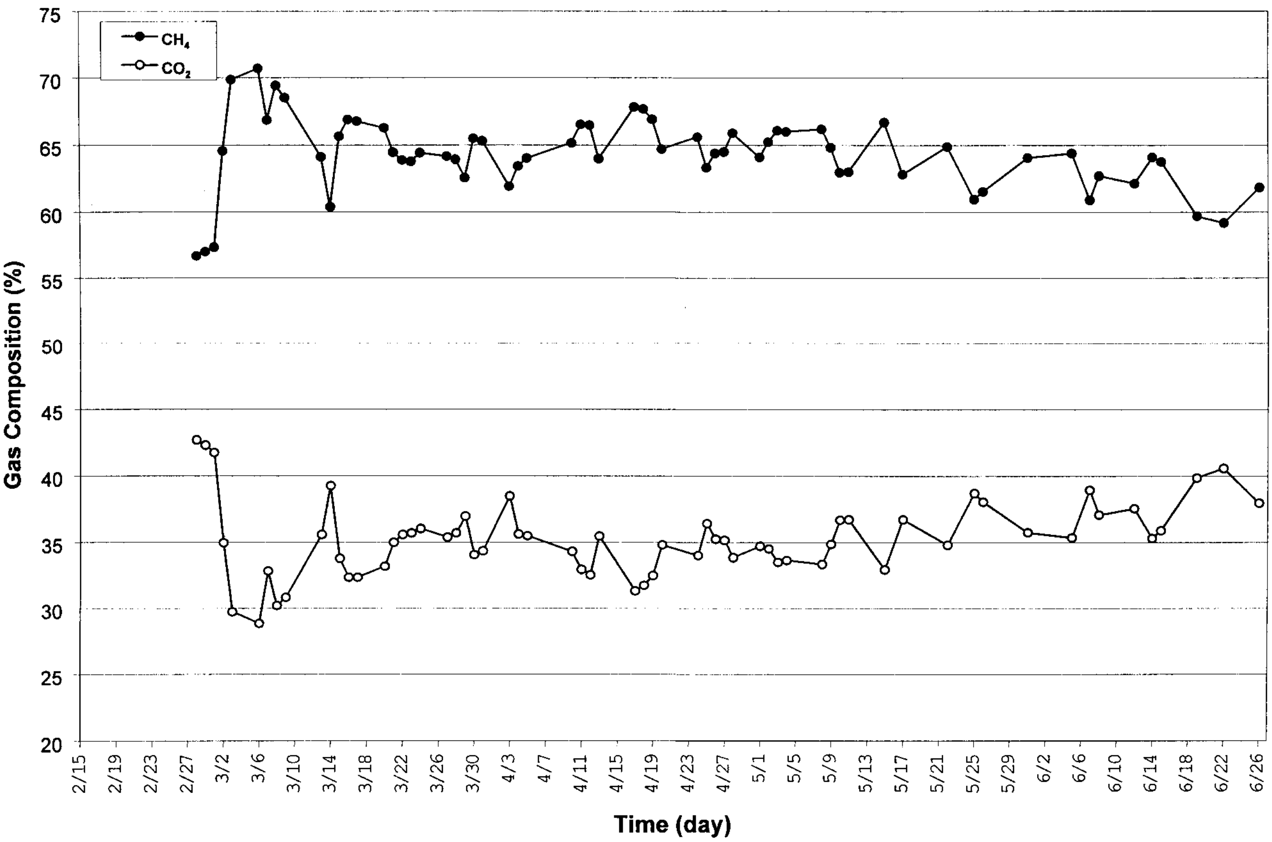

Figure 9—Time history of methane and carbon dioxide concentrations.

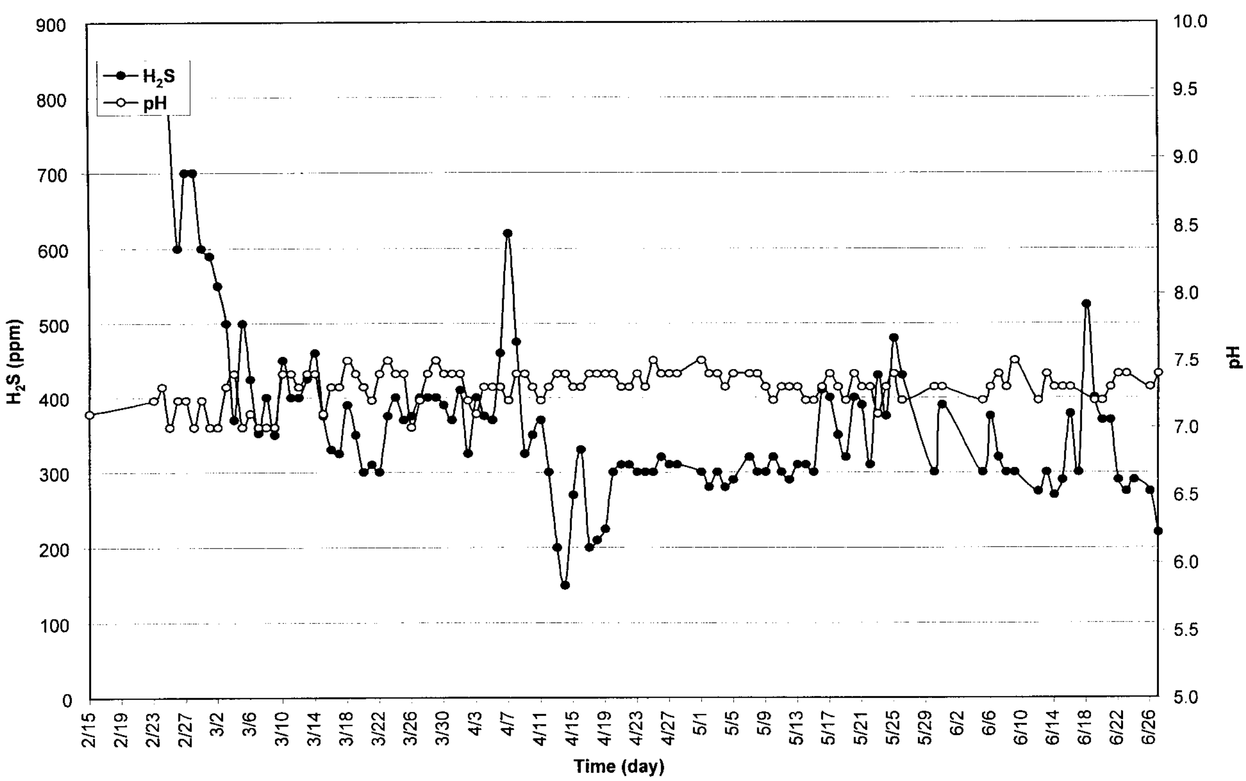

Figure 10—Time history of hydrogen sulfide concentrations and pHs.

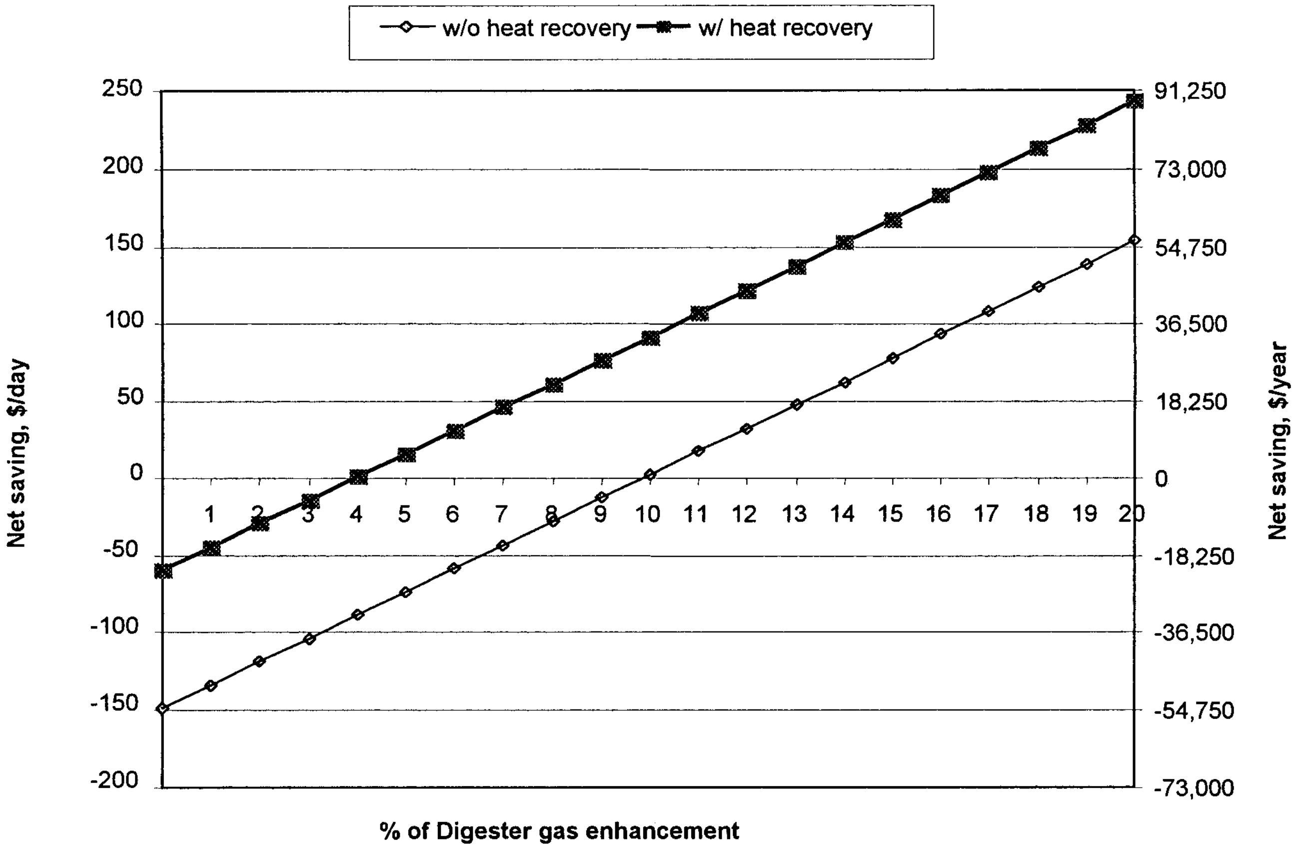

Figure 11—Economic analysis of mesophilic and thermophilic operations for TITP.

part of the effort to minimize the expenses of complying with legal requirements and is included in this paper to demonstrate that thermophilic operation need not be as expensive as commonly believed. However, demonstrating low costs was not a significant objective of the study, and no attempt was made to formulate the analysis for national or international applicability. Comparing the thermophilic and mesophilic operations at TITP shows that if the thermophilic gas production were higher than the mesophilic gas production by only a few percent, the thermophilic operation could be less expensive than the mesophilic. A key consideration is that an increase in the gas production results from increased destruction of volatile solids, which implies that less polymers are needed in the dewatering process and less wet cake needs to be stored and or transported. The change in costs results from the combination of these factors together with the increase in the value of the gas. Additional operational costs would be reduced in thermophilic operations if the heat from the digested sludge were recovered via a heat exchanger.

Figure 11 shows the net savings as a function of increase in gas production if thermophilic digestion without heat recovery were used at TITP instead of mesophilic digestion and shows the additional savings from heat recovery. These results are based on digester gas heating value of 24.2 MJ/m^3 (650 Btu/cu ft), a heating value price of $3.98/GJ ($4.20/mil Btu), polymer cost of $2.18/kg ($0.99/lb), steam cost of $0.0104/kg ($0.0047/lb), and hauling cost of $20.78/wet metric ton ($22.90/wet ton). A linear mass balance model was used. For an increase in gas production of 17%, the yearly savings at TITP would be approximately $39,500, or $100/d for no recovery; with recovery, the savings would double. The data in Table 5 imply that the typical TITP flow of 530 m^3/day (0.14 mgd) contains approximately 19 metric ton (42 $\times$ 10^3 lb) dry weight of total solids, or 14.5 metric ton (32 $\times$ 10^3 lb) of volatile solids, for respective daily savings of $5.26/metric ton total solids and $6.90/metric ton volatile solids with no heat recovery, or $10.52/metric ton and $13.80/metric ton, respectively with heat recovery (Iranpour and co-workers, 2001d).

An additional advantage of heat recovery from the digested sludge in a heat exchanger would be a reduction in odor (Kelly et al., 1999). Although this benefit has not been quantified, it has the potential for eventual economic payoffs by avoiding air quality actions by regulatory agencies and lawsuits from neighboring businesses.

Project Status. The digester is now operating successfully while being fed most of the plant's daily sludge production. The development of the culture has followed a course similar to that seen at many other successful thermophilic operations, with an initial rise of acid concentration (primarily acetate) as the acidogen activity initially exceeded the activity of the methanogens and a later decline and approximate stabilization of the acid concentration as the activities of the microbial communities came into balance. The chemical parameters have been nearly stable since early in the startup period, indicating that a biological community has been established that has been able to increase in numbers to meet the increases in the feed rate. Likewise, disinfection has been stably effective for several months, and the combination of low VFAs and low hydrogen sulfide is good news for odor control.

Potential Future Developments. It is believed that detailed chemical and biological monitoring like that used in the current project could provide insight to the operation of digesters under the conditions achieved in studies by the Greater Vancouver (Canada) Regional District (Peddie et al., 1996; Volpe et al., 1993). Such monitoring may also be helpful in analyzing two-phase anaerobic digestion systems (Ghosh, 1998; Hagley, 1998; Huyard et al., 1998; Meredith et al., 1998; Wilson and Dichtl, 1998) and inhomogeneous digesters (Chernicharo and Cardoso, 1999; Jeison and Chamy, 1999; Núñez and Martínez, 1999; Vossoughi et al., 2000).

Conclusions

Observations made during the study can be summarized as follows: (1) After the initial period of high concentrations, the VFA concentrations have stayed nearly stable despite several large increases in the feed rate. (2) The short-term pH and alkalinity fluctuations are well correlated, but both fluctuations are small. (3) The acid/alkalinity ratio has ranged from 0.1 to 0.25 since early March and has recently been less than 0.2. (4) The gas composition has been nearly stable at 60 to 65% methane and 35 to 40% carbon dioxide. (5) The decline in alkalinity after early May does not primarily represent consumption of buffering capacity by increased acid concentrations. (6) Hydrogen sulfide concentrations in the gas have been low since early March; long-term variations apparently corresponded to changes in the feed rate. (7) The coliform counts have exceeded the class A limit on only a few occasions, and, except for a questionable measurement in mid-June, the counts have held nearly steady since the middle of April at approximately 100 (i.e., one-tenth of the class A biosolids limit requirement). (8) A linear mass-balance model of the costs and the best available estimate of the enhancement in gas production suggest a reduction in operating costs of approximately $100/d.

Hence, in comparison with the initial objectives of the study, the following conclusions were reached: (1) A balanced culture was established in approximately two weeks and has been maintained despite several large increases in the feed rate. (2) Digester disinfection meets and exceeds the U.S. EPA class A general standard for fecal coliforms. (3) Volatile solids destruction and estimated gas production seem to have been greater than those obtained from mesophilic digestion, but the calculations of the changes are subject to large uncertainties. (4) The culture activity in the digester was increased enough to process approximately 80% of the plant's entire production of approximately 454 m^3/d (0.12 mgd) of thickened raw sludge while maintaining a balanced culture, class A disinfection, and satisfactory volatile solids destruction and gas production. Further increases in processing rate seem possible. (5) The initially chosen plan of rapid heating and gradual increase in digester feeding clearly achieved three of the first four objectives and has come close to achieving the fourth. (6) The chemical and physical state of the digester was monitored in abundant detail, but few difficulties arose and little corrective action was needed.

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