Thermophilic-Anaerobic Digestion to Produce Class A Biosolids: Initial Full-Scale Studies at Hyperion Treatment Plant

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ABSTRACT: The highest quality of biosolids is called exceptional quality. To qualify for this classification, biosolids must comply with three criteria: (1) metal concentrations, (2) vector-attraction reduction, and (3) the Class A pathogen-density requirements. The City of Los Angeles Bureau of Sanitation Hyperion Treatment Plant (HTP) (Playa del Rey, California) meets the first two requirements. Thus, the objective of this study was to ensure that HTP's biosolids production would meet the Class A pathogen-reduction requirements following the time–temperature regimen for batch processing (U.S. EPA, 1993; Subsection 32, Alternative 1). Because regulations require the pathogen limits to be met at the last point of plant control, biosolids sampling was not limited to immediately after the digesters, i.e., the digester outflows. The sampling extended to several locations in HTP's postdigestion train, in particular, the last points of plant control, i.e., the truck loading facility and the farm for land application.

A two-stage, thermophilic-continuous-batch process, consisting of a battery of six egg-shaped digesters, was established in late 2001 for phase I of this study and modified in early 2002 for phase II. As the biosolids were discharged from the second-stage digesters, the *Salmonella* sp. (pathogen) and fecal-coliform (indicator) densities were well below the limits for Class A biosolids, even though the second-stage-digester temperatures were a few degrees below the temperature required by Alternative 1. *Salmonella* sp. densities remained below the Class A limit at all postdigestion sampling locations. Fecal-coliform densities were also below the Class A limit at postdigestion-sampling locations, except the truck-loading facility (phases I and II) and the farm for final use of the biosolids (phase II). Although federal regulations require one of the limits for either fecal coliforms or *Salmonella* sp. to be met, local regulations in Kern County, California, where the biosolids are land-applied, require compliance with both bacterial limits. Additional work identified dewatering, cooling of biosolids after the dewatering centrifuges, and contamination as possible factors in the rise in density of fecal coliforms. These results provided the basis for the full conversion of HTP to the Los Angeles continuous-batch, thermophilic-anaerobic-digestion process. During later phases of testing, this process was demonstrated to produce fully disinfected biosolids at the farm for land application. *Water Environ. Res.,* **78,** 170 (2006).

KEYWORDS: thermophilic-anaerobic digestion, biosolids, Class A, exceptional quality, disinfection, fecal coliforms, *Salmonella* sp., vector-attraction reduction, postdigestion.

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Introduction

One of the priorities of the City of Los Angeles Bureau of Sanitation (California) is to produce biosolids of exceptional quality (EQ). To qualify for such classification, biosolids must comply with metal-concentration limits, a vector-attraction-reduction requirement, and the Class A pathogen-density-reduction requirement (U.S. EPA, 1993 and 1994b). Biosolids produced at the Hyperion Treatment Plant (HTP) have always met the first two requirements. Thus, the primary challenge to produce EQ biosolids is to ensure that the pathogen-density-reduction requirements are met at the last points of plant control, i.e., the truck-loading facility and the farm for land application.

There are six alternatives in the 40 *Code of Federal Regulations* (*CFR*) Part 503.32 rule (U.S. EPA, 1993 and 1994b), which gives the specifications for Class A biosolids. All alternatives have a general requirement that either the density of *Salmonella* sp. must be less than 3 MPN/4 g dry wt (weight) or the density of fecal coliforms must be less than 1000 MPN/g dry wt. Alternative 1 specifies that biosolids must be subjected to a defined time–temperature regime.

Thermophilic-anaerobic digestion has been recognized as more effective than mesophilic digestion for inactivation of pathogenic bacteria (Berg and Berman, 1980; Carrington et al., 1991) and is one option to achieve the time–temperature requirement for Class A biosolids. Recent bench-scale studies have confirmed these observations (e.g., Watanabe et al., 1997). A wide array of two-phase digestion processes, which combine anaerobic digestion of wastewater sludge and thermal treatment, have been tested and implemented at full-scale (Ghosh, 1998; Wilson and Dichtl, 1998). Whereas thermophilic digestion may achieve improved solids destruction, even though the digesters are operated at shorter hydraulic-retention times (HRTs) (Schafer et al., 2003), disinfection of biosolids to Class A standards has only been demonstrated in a few cases, with sampling generally done immediately after digestion, i.e., the digester outflows. With respect to the legal requirements, however, the sampling points should cover the last point of plant control. This could be interpreted as the truck-loading facility and/or the farm for land application.

The HTP has a long history of involvement with thermophilic digestion. The first prolonged operational use of thermophilic-sludge digestion in the United States was at HTP during the 1950s, and another test was conducted during the 1970s (Garber, 1954; Garber et al., 1975). These studies were similar to a wide variety of others during this period (e.g., Andrews and Pearson, 1965; Fair and Moore, 1934; McCarty, 1964; Pohland and Bloodgood, 1963), in being motivated, to a large degree, by the hope that the more rapid metabolism of thermophilic organisms would translate into advantages in digestion speed or operational efficiency, if process

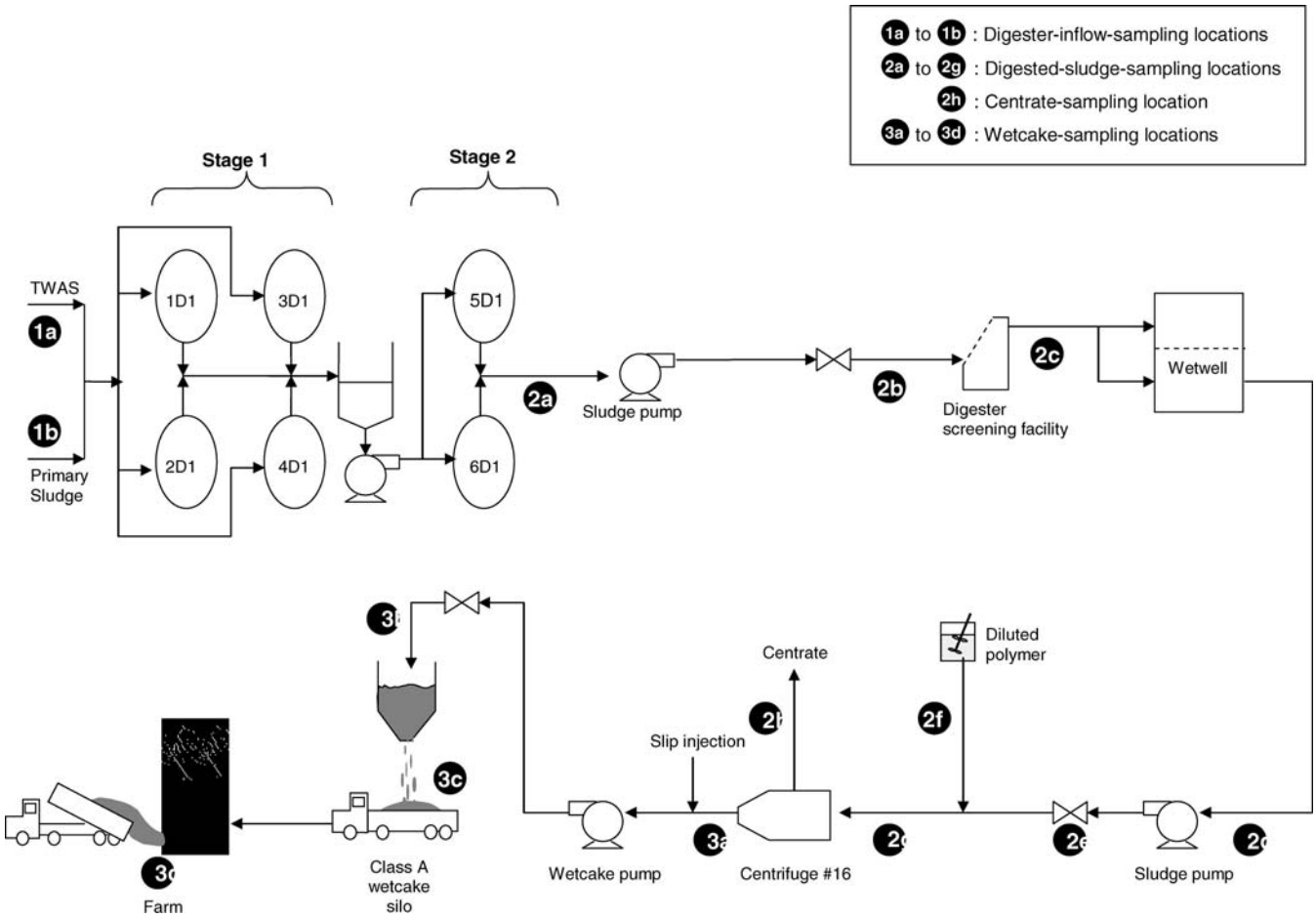

Figure 1—The HTP schematic for battery D1 thermophilic operations with dedicated postdigestion train, isolated from mesophilic operations.

stability could be maintained. Recent interest in thermophilic-anaerobic digestion at the HTP is driven by stricter regulations for removal of pathogens from wastes being digested for final use as a soil amendment (Ahring et al., 2001; Ghosh, 1998; Iranpour and Cox, 2005; Iranpour et al., 2002, 2004, 2005a, b, and c).

In early 2001, a battery of six digesters at the HTP was converted to thermophilic operation using a fast heating approach that was expected to produce a culture of true thermophiles (Shao et al., 2002) instead of thermotolerant mesophiles. As part of a series of experiments on these digesters, it was decided to use two of them as a second stage for batch processing to assure compliance with Alternative 1. This paper focuses on experiments conducted in late 2001 (phase I) and early 2002 (phase II).

The specific objectives for this project were the following:

(1) Implement a decontamination protocol to ensure elimination of mesophilic sludge in the thermophilic train.
(2) Establish a full-scale, two-stage, thermophilic-batch process that satisfies the time–temperature (Alternative 1) requirements for Class A biosolids, as indicated by U.S. Environmental Protection Agency (U.S. EPA) 40 *CFR* Part 503.32 (U.S. EPA, 1993). Phase I was to focus on sampling within the plant and to use a shorter holding time and a slightly higher temperature in the second stage than were used in phase II. Phase II was to expand sampling to the digester inflows and the farm, where the biosolids were applied to the land.
(3) Evaluate the effectiveness in the inactivation of pathogen (*Salmonella* sp.) and indicator (fecal-coliform) organisms by the two-stage process immediately after the digesters (digester outflows).
(4) Determine the effect of postdigestion processing on the densities of *Salmonella* sp. and fecal coliforms, in particular, in biosolids at sampling locations required by regulations (truck-loading facility and farm).
(5) Evaluate the biosolids-temperature profile and regrowth/contamination problems throughout the postdigestion train to identify potential solutions.

Materials and Methods

Operational Procedures. *Hyperion Treatment Plant.* The HTP is the main wastewater-treatment facility for the City of Los Angeles, servicing a 1554-km^2 (600-mi^2) area, with an approximate population of 4 million. The treatment process consists of preliminary screening and enhanced primary treatment, a pure-oxygen secondary-activated-sludge process, conventional and egg-shaped digesters, solid-bowl centrifuges for sludge dewatering, and biosolids handling and storage. The average daily flowrate is 1.4×10^6 m^3/d (360 mgd), with a design peak wet-weather flowrate of 3.2×10^6 m^3/d (850 mgd). The plant produced approximately 725 metric tons (wet weight) of Class B biosolids per day, all of

Table 1—Battery D1 digester cycles and pumping rates for thermophilic operations.

		Two stage digestion				
		Stage 1 (digestion) 1D1 to 4D1		Stage 2 (disinfection) 5D1 or 6D1		
		Continuous feed/withdraw		Batch feed/withdraw		
		Feed	Withdraw	Feed	Hold	Withdraw
Phase I October 4–16, 2001	Flowrates, m^3/min (gpm) Durations, hour	1.89 (500)	1.89 (500)	2.27 (600) 62	13	1.89 (500) 75
Phase II February 25–March 21, 2002	Flowrates, m^3/min (gpm) Durations (hour)	1.89 (500)	1.89 (500)	2.57 (680) 55	24	1.80 (475) 79

which were used for land application in Riverside and Kern counties. County ordinances, which forbid the land application of Class B biosolids as of the end of 2002, have led the City of Los Angeles to develop an ambitious program to convert its digesters to thermophilic operation for the production of EQ biosolids by the end of 2002.

Process Description. Figure 1 shows a schematic of the two-stage thermophilic operations. Each digester has a capacity of approximately 9500 m^3 (2.5×10^6 gal) and an internal draft-tube mixing system. Primary sludge, at 1.51 m^3/min (400 gpm), and thickened-waste-activated sludge (TWAS), at 0.38 m^3/min (100 gpm), were fed to the stage 1 digesters (1D1 to 4D1). The flows to these digesters were through electrically operated valves, which were programmed to open and close every few minutes on regular cycles, providing an average flow of 0.47 m^3/min (125 gpm) to each digester. Because the flow through these digesters is continuous, it is important that the mixing system minimizes short-circuiting, so that very nearly all of the sludge is retained long enough for satisfactory digestion and disinfection. The feed pipes are located approximately halfway up the sides of the digesters (at 16 and 17 m [53 and 56 ft] above the bottom, respectively, for the primary sludge and TWAS feeds, out of a total height of 35 m [115 ft]). The withdrawal pipes are at heights of 1.8 and 32 m (6 and 105 ft). The feed mixture, at approximately 21°C, was heated by steam in the stage 1 digesters and digested under thermophilic conditions, with an average detention time of 13 days.

The digested sludge from the stage 1 digesters was then pumped into one of the stage 2 batch digesters (5D1 or 6D1), for a final holding period, to make sure that the time–temperature relation in Alternative 1 was met. The cycle times and pump rates are shown in Table 1. The feeding was through a pipe at 16 m (53 ft) above the bottom, and withdrawal through a pipe at 1.8 m (6 ft). Once the batch digester was filled and the contents were held for the planned time, the pump after the stage 2 digesters was switched to fill the other stage 2 batch digester. A wet well provided temporary storage for the outflow from the stage 1 digesters during the holding periods. After stage 2, sludge was pumped to the digester-screening facility (0.1-mm static screens) for removal of hair, fibers, rags, grits, and other impurities. Screened sludge then flowed by gravity to a wet well. Diluted polymer solution was injected downstream of the wet-well pump and mixed into the sludge through an inline static mixer before the mixture was fed to the dewatering centrifuge. The wet cake from the centrifuge (with a solid content of approximately 28%) was then pumped to the wet-cake silo at the truck-loading facility.

Heating of sludge was done by steam injection, which was limited to the first-stage digesters, because reliable temperature control and steam injection required a constant (and high) sludge level in the digesters. Target temperatures in the first-stage digesters were, therefore, a few degrees higher than the ones in the second stage, to allow for some cooling between the two stages. In phase I, the target temperature in the second stage to meet the Alternative 1 relation with a holding time of 13 hours was 57°C. On the first few days of this period (from October 1 to 4), the stage 1 target temperature was 55 to 56°C, but was gradually increased to approximately 60°C on the later days of phase I. In phase II, the target temperature, in the second stage for the holding time of 24 hours, was 55°C, so the stage 1 target temperature was 57.2 to 57.8°C. Actual temperatures in the digesters were continuously recorded using resistance-temperature probes located in the upper part of each digester.

Decontamination of Thermophilic Train. A protocol to ensure elimination of contaminating mesophilic sludge in the thermophilic train was implemented. For phase I, lines from battery D to the centrifuge-centrate outlet were flushed with secondary effluent, at high pressure. The centrifuge, the C-7 wet well, and the silo were

Table 2—Phase I thermophilic-process performance.

Parameter	Mean	Standard deviation	Range
Primary sludge			
Total solids (%)	3.0	0.2	2.5 to 3.4
Volatile solids (% of TS)	77.6	1.3	73.2 to 80
TWAS			
Total solids (%)	5.1	0.6	2.7 to 6.2
Volatile solids (% of TS)	81	1.9	71.7 to 83.1
Digester outflow			
Total solids (%)	1.88	0.24	1.66 to 2.5
Total-solids destruction (%)	50.4	4.5	33.5 to 57.8
Total-volatile-solids destruction (%)	57.9	3.9	45.4 to 63.7
pH	7.16	0.1	6.9 to 7.3
Total-volatile-fatty acids (mg/L)	656	303	206 to 1083
Alkalinity (mg/L)	3496	155	3318 to 3700
Volatile-fatty-acids-to-alkalinity ratio	0.19	0.09	0.07 to 0.32

Table 3—Phase I heavy-metal concentrations (mg/kg dry wt) in HTP biosolids.

Pollutant	Phase I biosolids			Limit concentration for EQ (Table 3 in 40 *CFR* 503.13; U.S. EPA, 1993)	Ceiling concentration (Table 1 in 40 *CFR* 503.13; U.S. EPA, 1993)
	Mean	Standard deviation	Range		
Arsenic	6.76	2.56	2.43 to 11.4	41	75
Cadmium	18.65	3.27	15 to 26.9	39	85
Chromium	109.82	15.9	89.7 to 141	—	—
Copper	877.58	77.34	743 to 990	1500	4300
Lead	48.99	11.34	33.5 to 70	300	840
Mercury	2.47	0.62	1.3 to 3.62	17	57
Molybdenum	22.33	4.73	15.3 to 30.8	—	75
Nickel	89.64	14.88	65.8 to 120	420	420
Selenium	9.57	6.73	0.6 to 19	100	100
Zinc	1123.5	96.8	956 to 1260	2800	7500

cleaned in place. The silo header was purged with thermophilic sludge. Complete separation of the thermophilic train from mesophilic operations was established, and a 24-hour, continuous-thermophilic feed was maintained. For phase II, decontamination was done by flushing with a hypochlorite solution. All parts were in contact with chlorine for at least several hours. The truck was cleaned by steam.

Sampling Procedures. Sampling locations (1a and b, digester inflow; 2a, b, c, d, e, f and g, between digester and dewatering centrifuge; 2 hours, centrate; 3a, b, c, and d, after dewatering centrifuge) are shown in Figure 1. At each sampling event, samples were collected in a separate, sterile bottle for the analysis of *Salmonella* sp. and fecal coliforms. An additional sample was taken for total-solids analysis. Sampling equipment was sterilized with 70% ethanol before use. Sample collection and preservation was performed according to procedures as described in Part 9020 of *Standard Methods* (APHA et al., 1992) and by U.S. EPA (1999).

Analytical Methods. Total solids and *Salmonella* sp. and fecal-coliform densities were measured following Parts 2540G, 9260, and 9221E.2 of *Standard Methods* (APHA et al., 1992), respectively. An outside certified laboratory (BioVir Laboratories, Benicia, California) measured the *Salmonella* sp. densities. Fecal-coliform densities were measured at the Environmental Monitoring Division laboratory at the HTP.

Process performance was monitored, during the early stages, with intermittent checks later to verify process stability. Volatile solids, total-volatile-fatty acids, pH, and alkalinity were determined according to Parts 2540E, 5560C, 4500-H^+ B, and 2320B of *Standard Methods* (APHA et al., 1992), respectively. Metal concentrations in biosolids were determined after digestion (U.S. EPA method 3050B; U.S. EPA, 1996) by graphite-furnace-atomic-absorption spectrophotometry (U.S. EPA method 200.9; U.S. EPA, 1994a) or inductively-coupled-plasma-atomic-emission spectrometry (U.S. EPA method 6010; U.S. EPA, 1996).

Additional Studies in Postdigestion Train. *Temperature-Profile Study.* Temperature profiles along the postdigestion train were determined by using a digital thermometer and recording temperatures of digested sludge and wet-cake samples at various locations, as indicated in Figure 1. This was done on a selected day during phase I, but, for phase II, temperatures were measured with every sample over the whole testing period. All measurements were done in triplicate.

Table 4—Phase I battery D1 digester temperatures.

	Temperature (°C)					
	Stage 1 (digestion)				Stage 2 (disinfection)	
	Continuous feed/withdraw				Batch feed/withdraw	
	1D1	2D1	3D1	4D1	5D1	6D1
Average	58.1	58.1	57.6	57.8	54.3	54.5
Standard deviation	1.6	1.5	1.5	1.8	1.8	0.9
Minimum	55.0	55.0	55.6	54.4	52.2	53.9
Maximum	60.6	60.6	60.6	60.6	56.7	56.1

Table 5—Phase I *Salmonella* sp. densities (MPN/4g dry wt); sampling locations in Figure 1.

Date (2001)	Digester inflow		Digested sludge*	Wet cake*	
	Location 1a (TWAS)	Location 1b (primary sludge)	Location 2a (digester outlet)	Location 3a (after centrifuge)	Location 3c (truck loading)
October 1			<1.3	<1.4	
October 2					<1.6
October 3			<1.8	<1.5	
October 4					<1.8
October 9			<1.8	<2.1	<2.1
October 10			<2.2	<1.7	<1.5
October 11			2.5	<1.3	<1.5
October 15			<2	<1.3	<1.4
October 16			1.8	<1.5	<1.4
November 8	<2.6	5.1			
November 13	1.8	3.3			
November 14	4.4	11			
November 15	<2.4	13			
November 19	<2.4	>18			
November 20	<2.4	7.7			
November 26	2.3	7			
November 27	2.1	11.4			
November 28	<2.1	>10.6			

* No sampling at locations 2e (after digested-sludge pump), 2g (before centrifuge), and 3d (farm).

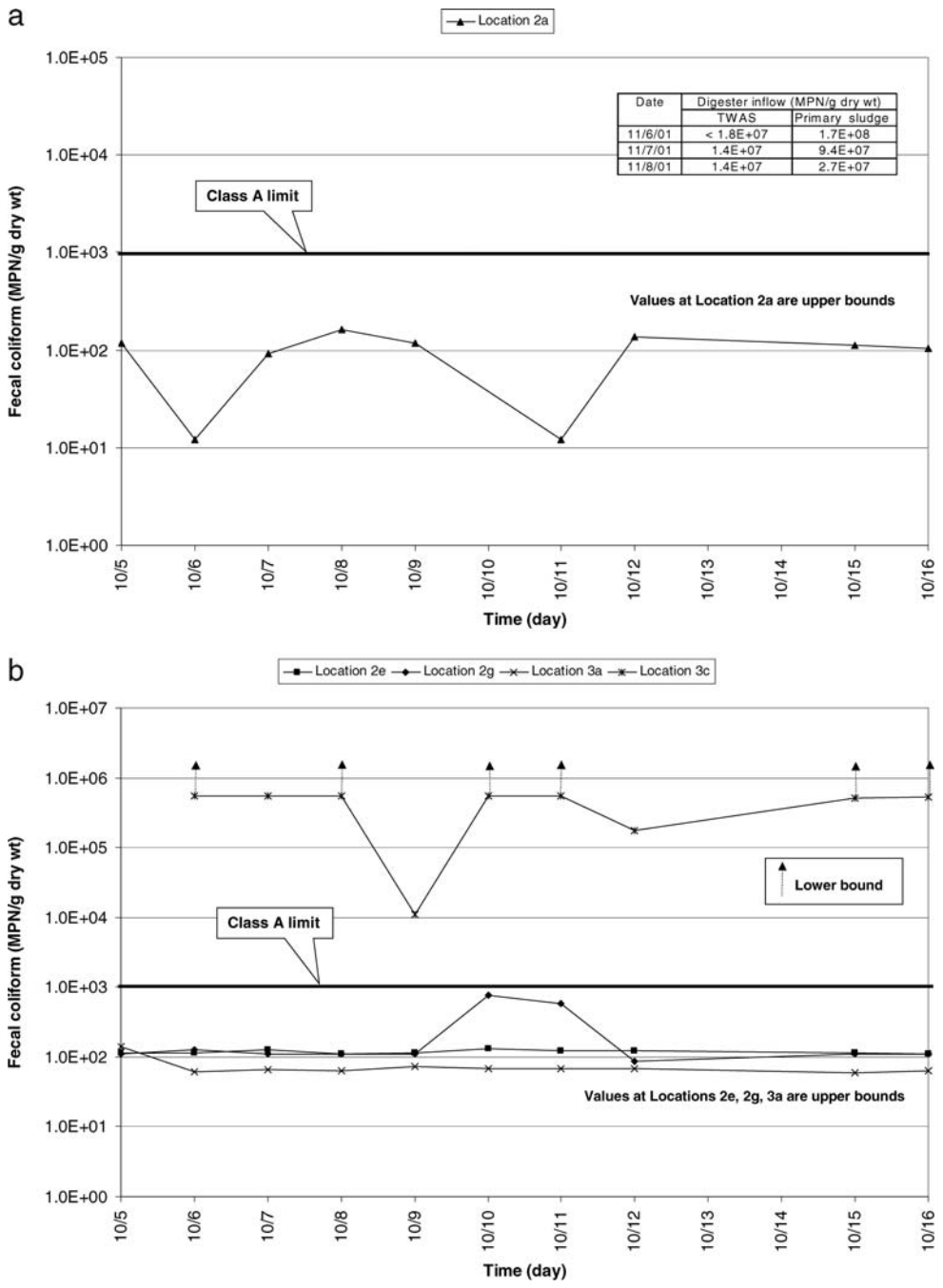

Figure 2—(a) Phase I fecal coliform before and after digestion; sampling locations in Figure 1; (b) Phase I fecal coliform in postdigestion; sampling locations in Figure 1.

Regrowth Study. Wet-cake samples from the centrifuge and truck-loading facility were collected in sterile capped bottles, which were left loosely capped to simulate conditions in the silo and the truck. Incubation was at room temperature, and samples were analyzed at selected times for *Salmonella* sp. and fecal-coliform densities.

Results

Process Performance. Digester inflow and outflow are routinely analyzed at the HTP to evaluate the performance of the digesters. The digestion observations during phase I are summarized in Table 2. They demonstrate that the thermophilic operation achieved total- and volatile-solids destruction similar to or slightly greater than those commonly observed in mesophilic operation, with alkalinity similar to that in mesophilic digesters, but somewhat higher total-volatile-fatty acids.

Metal Pollutants and Vector Attraction. Table 3 lists the results of analyses conducted on thermophilically digested biosolids for the metal pollutants specified in 40 *CFR* Part 503.13 (U.S. EPA, 1993). The next to the last column in Table 3 includes the legal limits of these pollutants for EQ biosolids, whereas the first column gives the average concentrations in HTP biosolids as determined

Table 6a—Phase I temperature profile along post-digestion train; locations in Figure 1.[a]

Location	Temperature (°C)	ΔT (°C)[b]	Ambient temperature (°C)
2a Digester 5D1 outlet	51.4	—	25.8
2b Before screening facility	50.8	−0.6	
2c After screening facility	50	−0.8	15.4
2d After dice II wet well	50.8	0.8	20.7
2f (Diluted polymer)	24.4	—	
2g Mixture of digested sludge and polymer	48.6	−2.2	
3a Centrifuge outlet	50.4	1.8	
2h (Centrate)	49.8	—	
3b Before falling into silo	43.6	−6.8	19.6

[a] Notes: Measurements were done on the same day (December 5, 2001). Digester (5D1) temperature was 51.1°C.
[b] Change in temperature (ΔT) is calculated with reference to the previous location.

over several months of operation. The last column in the table gives the ceiling concentrations, which are the maximum concentration limits for all classes of biosolids for land application. Clearly, the results from the thermophilic samples were well below all the U.S. EPA limits. As shown in Table 2, thermophilic digestion also always exceeded the 38% minimum for volatile-solids destruction to meet the vector-attraction reduction standard in 40 *CFR* Part 503.33. Hence, meeting the Class A pathogen-reduction standards determines whether the biosolids have EQ.

Disinfection—Phase I. *Digester Temperatures.* Temperatures in the first-stage digesters slowly increased from approximately 55 to 60.5°C during phase I, as indicated by the measured range of digester temperatures in Table 4. The average temperature in the first stage was 58°C, with very little difference between individual digesters. Temperatures in the second-stage digesters were a few degrees Celsius lower (on average 54.4°C) because of heat losses during sludge transport from the first to second stage and during holding without heating in the second-stage digesters.

Digester-Disinfection Efficiency. Average densities of *Salmonella* sp. in the primary sludge and TWAS were approximately 10 MPN/4 g dry wt and 2.5 or less MPN/4 g dry wt, respectively, but they were consistently below the Class A limit after digestion and often nondetectable, as indicated by the upper-bound values in Table 5. Levels of fecal coliforms before and after digestion are shown in Figure 2a. A large number of fecal coliforms (approximately 10^7 to 10^8 MPN/g dry wt) was observed in both components of the digester inflow, but the densities after digesters met the Class A requirement.

Postdigestion-Temperature Profile. Table 6a shows the temperature profile obtained along the postdigestion-thermophilic train. The difference in temperature between a given location and the previous one is indicated in Table 6a as ΔT. The largest drop in temperature (ΔT = −6.8°C) was observed between locations 3a (centrifuge outlet) and 3b (before falling into silo). Table 6b shows the temperature profile obtained on three different days at the truck-loading location. Wet-cake temperatures obtained at the front and at the rear of the truck correspond to wet cake located at the lowest level of the silo and at a higher level, respectively. The data indicate that the lowest temperature of wet cake was found at the lowest level of the silo. The differences in temperature (ΔT) between the lower (truck front sample) and the higher level (truck rear sample) in the silo ranged from 1.2 to 4.9°C.

Postdigestion-Bacterial Regrowth. The *Salmonella* sp. counts at sampling locations 2a, 3a, and 3c in the postdigestion train are reported in Table 5. Samples from locations 2e and 2g were not obtained because they were not considered relevant and omitting them reduced sampling costs. Levels of *Salmonella* sp. measured at the three sampling locations, including the truck-loading facility (location 3c), were consistently below the U.S. EPA Class A limit of 3 MPN/4 g dry wt.

Densities of fecal coliforms in samples taken at the five locations throughout the postdigestion train at HTP are shown in Figures 2a and 2b. They indicate that fecal-coliform concentrations were consistently below the U.S. EPA Class A biosolids limit at locations 2a, 2e, 2g, and 3a. It is of particular interest that densities of fecal coliforms in the wetcake at location 3a were consistently lower (typically <72 MPN/g dry wt) than the pre-centrifugation densities. Because the digester-screening facility removes almost everything except cellular material and because very little of this material is lost in the centrate, the observed reduction in the density of viable coliforms resulting from centrifugation must be understood as killing, rather than physical removal. Determinations of the fecal-coliform density in the centrate to confirm this hypothesis were not performed.

No increase in counts was observed in the centrifuge wet-cake samples when incubated for up to 400 hours at ambient temperature during laboratory-regrowth studies (Figure 3). This indicates that the centrifuge wet cake did not contain viable fecal coliform. A

Table 6b—Phase I temperature profile at truck-loading facility; Location 3c, Figure 1.

Date (2001)	Time	Time elapsed[a] (h)	Truck location (°C)	Temperature (°C)	ΔT[b] (°C)	Silo level (m [ft])		Ambient temperature (°C)
						Before	After	
December 6	7:20 AM	15	Front	39.9		5.6 (18.4)	4.0 (13.1)	12.0
			Rear	44.8	4.9			
December 7	9:25 AM	41	Front	44.4		4.0 (13.1)	2.9 (9.6)	18.6
			Rear	45.6	1.2			
December 10	10:00 AM	114	Front	36.9		2.9 (9.6)	1.6 (5.2)	14.8
			Rear	39.7	2.8			

[a] Wet-cake-storage duration in the silo after measuring the temperature on December 5, 2001 (Table 6a).
[b] Difference in temperature (ΔT) between the rear and front samples.

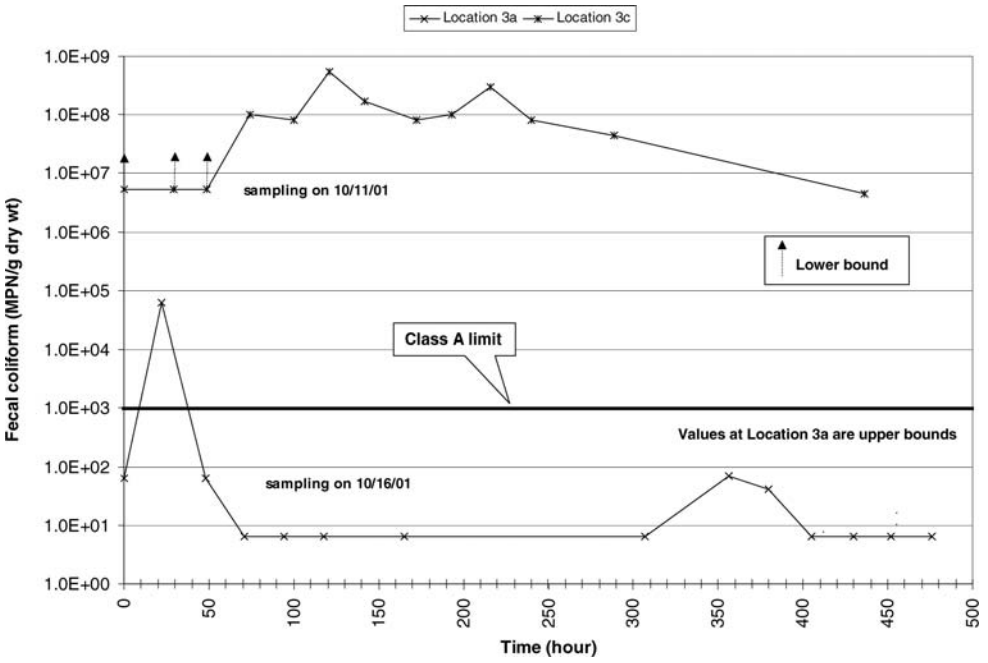

Figure 3—Phase I regrowth of fecal coliform; sampling locations in Figure 1.

significant increase in the density of fecal coliforms was observed at the truck-loading facility, where the numbers were high (10^6 MPN/g dry wt) in wet-cake samples at the truck. They increased up to 10^8 MPN/g dry wt during subsequent storage in the laboratory (Figure 3). However, after approximately 400 hours incubation during regrowth studies, the counts decreased to the initial levels. The implications of these regrowth studies will be discussed in the Discussion section.

Disinfection—Phase II. *Digester Temperatures.* Average daily temperatures in the digesters are presented in Table 7. The first-stage digestion temperature in the four digesters was, on average, 57.7°C, which was nearly identical to the preset target temperature of 58.3°C. Temperatures during second-stage batch processing were, on average, 1.6°C less than required (55°C at 24-hour holding) under Alternative 1 of 40 *CFR* Part 503.32 (U.S. EPA, 1993). Cooling of sludge, after first-stage digestion during phase II, appeared to be slightly more than during phase I (4.2 vs. 3.5°C). The average ambient temperature (daily maximum) during phases I and II was 22.3 and 18.5°C, respectively. Cooling, resulting in suboptimum second-stage temperatures, might, in the future, be resolved by increasing the steam supply to the first-stage digesters or adding steam to the feed lines before the second-stage digesters, and by insulation and heat-tracing of transport lines in postdigestion.

Digester-Disinfection Efficiency. As in phase I, densities of *Salmonella* sp. and fecal coliform in primary sludge and TWAS were above the limits imposed on biosolids for Class A qualification (Table 8 and Figure 4a). Two-stage thermophilic digestion consistently reduced these microbial densities to a nondetectable level (*Salmonella* sp.) or well below the allowed maximum (fecal coliform), as indicated by the digester-outlet data in Table 8 and Figure 4a, respectively.

Postdigestion-Temperature Profile. Postdigestion processing caused further cooling of the digested sludge (Table 9). The largest temperature drop was between the centrifuge and the silo, with the average temperature decreasing from 48.2 to 41.0°C. Cooling during transport to the farm was relatively insignificant. The average wet-cake temperature upon arrival at the farm was 40.3°C.

Postdigestion-Bacterial Regrowth. Analyses of samples along the postdigestion train indicated that the density of *Salmonella* sp. remained well below the U.S. EPA limit of 3 MPN/4 g dry wt at all sample locations, including at the farm, when the wet cake and biosolids were unloaded (Table 8). Fecal-coliform densities in the centrifuge wet cake were also below the U.S. EPA limit, but a significant increase was observed in wet-cake samples taken at the truck-loading facility and the farm (Figure 4b).

Discussion

The common bacteriological requirement of all the alternatives in 40 *CFR* 503.32 is that, when the biosolids are at the last points of plant control, i.e., being loaded onto the trucks and/or land-applied at the farm, *either* the coliform density *or* the *Salmonella* sp. density is to be below the respective limits specified for these types of organisms. Because the density of *Salmonella* sp. is less than 3MPN/4 g dry wt at all postdigestion sampling points, this requirement is satisfied.

Table 7—Phase II battery D1 digester temperatures.

	Temperature (°C)					
	Stage 1 (digestion)				Stage 2 (disinfection)	
	Continuous feed/withdraw				Batch feed/withdraw	
	1D1	2D1	3D1	4D1	5D1	6D1
Average	57.8	58.0	57.7	57.1	53.7	53.2
Standard deviation	1.1	1.1	1.6	1.0	1.1	1.5
Minimum	55.4	56.2	54.1	55.8	51.4	46.6
Maximum	59.6	60.4	60.1	60.2	55.2	55.5

Table 8—Phase II *Salmonella* sp. densities (MPN/4g dry wt); sampling locations in Figure 1.*

	Digester inflow		Digested sludge	Wet cake		
Date (2002)	Location 1a (TWAS)	Location 1b (primary sludge)	Location 2a (digester outlet)	Location 3a (after centrifuge)	Location 3c (truck loading)	Location 3d (farm)
February 25	2.4	>8.5				
February 26	<2	2.6				
February 27	<1.6	>12.5				
March 4	<2.2	>10.2	<2.5	<1.1		
March 5	2.1	10.1	<2	<1.1	<1.2	1
March 6	>17.1	11.2	<2.6	<2.1		
March 7	<2	10.2	<1.9	<1.8	1.5	<1.5
March 11	5.1	10.7	<1.9	<1.7		
March 12	<2.2	10.1	<1.7	<1.5	<1.1	
March 13	<2.2	3.3	<1.9	<1.8		
March 14	<2.3	>9.8	<1.8	<1.8	<1.5	<1.5
March 18			<2	<1.9		
March 19			<1.9	<1.9	1.9	<1.8
March 20			<1.8			
March 21					<1.5	

* No sampling at locations 2e (after digested-sludge pump) and 2g (before centrifuge).

Successful reductions of bacterial densities have been reported in other two-stage, anaerobic-digestion processes containing at least one high-temperature stage. However, the sampling locations have been immediately after the digesters, i.e., the digester outflows. For example, Volpe et al. (1993) reported that Class A fecal-coliform standards were consistently achieved by a two-stage, continuous-flow-thermophilic digestion (20 days HRT for each stage) that was implemented at the Lion's Gate Plant of the Greater Vancouver Regional District (Vancouver, British Columbia, Canada). Huyard et al. (1998) also found fecal-coliform densities below 10^3 MPN/g dry wt, after treatment in a pilot unit provided with a thermophilic reactor (55 to 60°C, 2 days HRT), followed by a mesophilic reactor (37°C, 10 days HRT). Fecal-coliform-log removals (MPN/g dry wt) were 5 and 0.67 after the thermophilic and the mesophilic reactors, respectively.

The additional requirements in the various alternatives for pathogen reduction are intended to ensure that also the densities of nonbacterial pathogens in biosolids are reduced to nondetectable levels to guarantee public safety. As opposed to the requirements for samples and assays specified in Alternatives 3 and 4, Alternatives 1, 2, and 5 specify processes, which have been found by previous microbiological testing to reduce the densities of viable human pathogens to undetectable levels, and Alternative 6 allows for other processes to be certified as meeting the disinfection standards after suitable testing. The goal of this study of thermophilic digestion has been to meet the time–temperature requirements of Alternative 1, which are believed to provide disinfection well below the limits of detection.

Most of the batch-digester temperatures in Table 4 were a few degrees below the minimum temperature of 57°C required for holding of 13 hours because of ongoing modifications of the steam supply to the digesters. Likewise, batch-digester temperatures during phase II were a few degrees below the minimum temperature of 55°C for 24 hours holding. Therefore, the time–temperature requirement of Alternative 1 for batch holding was not met in either phase.

Several potentially significant considerations have arisen in trying to understand the large densities of fecal coliforms observed at the truck-loading facility. The large temperature drop between the centrifuge outlet and this facility might have facilitated the increase in fecal-coliform counts. Additionally, the regrowth-and-contamination experiments suggest that microbial contamination might have occurred between the centrifuge and the truck-loading location. Potential sources of bacterial contamination are the ambient air in the silo, the effluent used to lubricate the pipelines that transport the wet cake to the silo, and the polymer added during dewatering. The results, to date, do not clearly identify a contamination source, and further research on this matter is warranted.

Watanabe et al. (1997) suggested an additional role for the polymer in the control of fecal coliforms in biosolids. They reported, in a large survey in Japan, that all of the treatment plants in which a large number of fecal coliforms were detected in dewatered sludge used polymer-type coagulant. In contrast, the number of bacteria in dewatered sludge from treatment plants using inorganic coagulants was approximately 1 MPN/g dry wt, without exception. Watanabe et al. (1997) suggested that the use of inorganic coagulants, such as lime, might be effective in inactivating fecal-coliform groups in dewatered sludge. It is also possible that the decomposition of polymer-type coagulants promotes the growth of pathogens. More research is needed to confirm the suggested roles of either type of coagulant and the practical implications for dewatering at HTP.

It is intriguing that fecal-coliform counts increased at the truck-loading facility, but *Salmonella* sp. counts did not increase. This observation might be an indication of the existence of an additional factor that prevents *Salmonella* sp. growth along the postdigestion train but does not cause the same inhibition of fecal coliforms.

One possible factor is antagonism between bacterial populations present in thermally treated sludge. Ward et al. (1999) reported *Salmonella* dieoff when this pathogen was added to an active mesophilic, bench-scale digester. They proposed that the presence of active mesophilic-anaerobic bacteria might cause the observed dieoff. Some antagonistic mechanisms that have been proposed are the toxic effect of metabolites characteristic of the anaerobic digestion, such as ammonia, volatile-fatty acids, or hydrogen-sulfide production (Lund et al., 1996), or inhibitory substances, such as bacteriocins and other secondary metabolites produced by other bacteria (Coventry et al., 1997). Similar products and metabolites

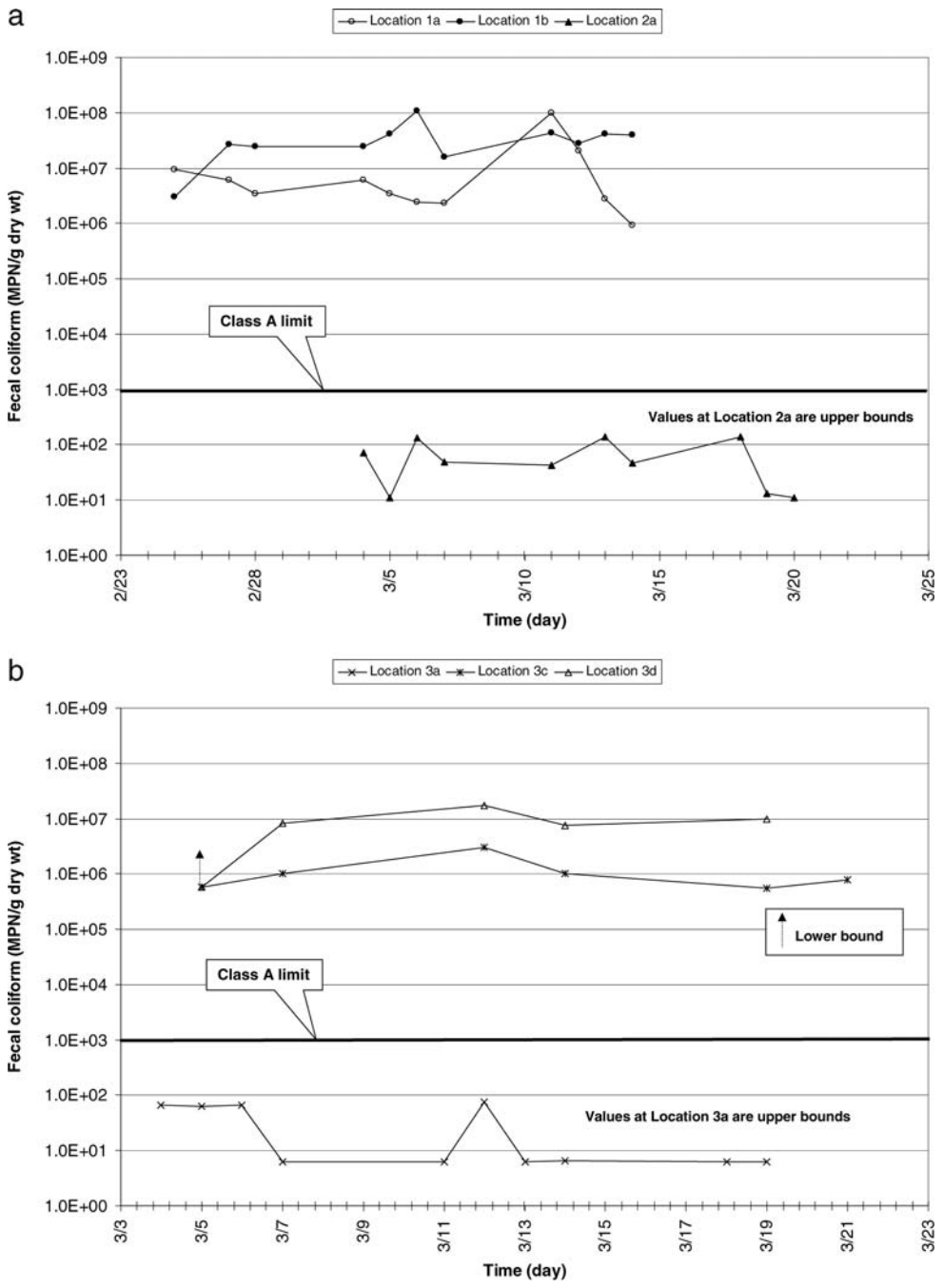

Figure 4—(a) Phase II fecal coliform before and after digestion; sampling locations in Figure 1; (b) Phase II fecal coliform in postdigestion; sampling locations in Figure 1.

are expected to be present in thermophilic digestion, but much remains to be learned about the biological interactions responsible for the behavior that we and others have observed.

Therefore, the high counts of fecal coliforms found in the wet cake at the truck-loading facility may be a result of a combination of factors, i.e., the drop in biosolids temperature, a contamination problem that occurred between the centrifuge and the truck-loading facility, and the absence of an antagonistic factor that helps to prevent fecal-coliform regrowth. Further studies are needed to determine the relative importance of these factors so that appropriate measures can be taken to reduce the coliform counts in the delivered biosolids.

Conclusions

The following conclusions can be made from this work:

(1) This work is one of the first studies to demonstrate the importance of extending the analyses of biosolids to the postdigestion train. Federal regulations require compliance with the Class A requirements in biosolids only at the last point of

Table 9—Phase II temperature profile along post-digestion train (sampling locations in Figure 1).*

	Temperature (°C)			
	Digested sludge	Wetcake		
Date (2002)	Location 2a (digester outlet)	Location 3a (after centrifuge)	Location 3c (truck loading)	Location 3d (farm)
March 4	54.1	51.4		
March 5	52.2	48.3	40.6	40.0
March 6	52.8	47.2		
March 7	51.7	47.8	42.8	41.7
March 11	52.8	47.8		
March 12	50.6	48.9	42.2	43.2
March 13	52.2	48.3		
March 14	53.3	47.2	37.8	38.9
March 18	52.8	47.2		
March 19	53.6	47.5	40.6	37.6
March 20			42.2	
Average	52.6	48.2	41.0	40.3
Standard deviation	1.0	1.3	1.8	2.2

* Note: Temperature measurements were done in samples for total-solids analysis.

plant control (the truck-loading facility and the farm for land application); hence, it should be ascertained that postdigestion processing does not result in exceedance of the Class A density limits that were met during thermophilic-anaerobic digestion.

(2) Digester-outflow samples of the two-stage, thermophilic-digestion process demonstrated reduction of *Salmonella* sp. and fecal-coliform densities to levels below the Class A federal standard, 40 *CFR* Part 503.32 (U.S. EPA, 1993), although the time–temperature relation for batch treatment (Alternative 1) was not met.

(3) Additional testing along the thermophilic-postdigestion train showed that *Salmonella* sp. densities remained below the Class A limit at all the sampling locations, including the last points of plant control (the truck-loading facility and the farm for land application).

(4) Additional testing along the thermophilic-postdigestion train showed that fecal-coliform densities also remained below the Class A limit at all sampling locations, except at the last points of plant control (the truck-loading facility and the farm for land application).

(5) Fecal-coliform regrowth or contamination occurred between the centrifuge outlet and the silo at the truck-loading facility. A preliminary profile of the biosolids temperature throughout the postdigestion train showed a large drop in temperature between the centrifuge and the silo at the truck-loading facility, which might have allowed the increase in fecal-coliform counts.

Future Directions

Based on the results of phases I and II, above, it has been decided for a 100% conversion of HTP to thermophilic-anaerobic digestion for Class A biosolids production. The conversion of a total of 20 egg-shaped digesters to the Los Angeles continuous-batch, thermophilic-anaerobic-digestion process will be completed in late 2002, after which further testing will commence. It is expected that fecal regrowth or contamination observed in phases I and II will be resolved: (a) once full conversion to thermophilic digestion has been completed and mesophilic biosolids are no longer produced; and (b) all biosolids transfer lines and the storage silos have been insulated and heat-traced to prevent temperatures in the postdigestion train from dropping to values that could allow the regrowth of fecal coliforms. Results of phases III, IV, and V testing have been submitted for publication (Iranpour and Cox, 2005; Iranpour et al., 2005c).

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