PILOT PLANT INVESTIGATION OF THERMOPHILIC-MESOPHILIC DIGESTION FOR A FULL-SCALE RETROFIT

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ABSTRACT

King County Wastewater Treatment Division has studied the use of temperature-phased anaerobic digestion at the West Point Treatment Plant (WPTP) in order to improve volatile solids destruction and/or to accommodate a reduced hydraulic residence time in the existing digesters. At WPTP, a specific objective is the elimination of one or more of the existing digester tanks. The pilot study has been conducted with two, 1900-L digesters, simulating the temperature-phased process with the first thermophilic stage operated at 55 ^{o}C and the second mesophilic stage at 35 ^{o}C. The pilot study was initiated in July, 1999, and operated for more than a year at loadings that were selected based on projected future loads and the removal of an existing digester. Specific loading conditions include normal average loading, average with one digester out of service for cleaning, and peak week and peak day conditions. The hydraulic retention times (HRT) tested include 12 day thermo-12 day meso, 8 day-8 day, 4 day-8 day, 2 day-12 day, a peak week of 5 day-5 day, and a peak day of 2.5 day-2.5 day. An initial phase tested the parallel operation of thermophilic and mesophilic digesters at a 20 day HRT.

In all operating conditions, the pilot digesters were fed combined primary and waste activated sludge that had been prethickened to approximately 6 % total solids (TS) with WPTP's gravity belt thickeners. Feeding and effluent removal was performed in a draw and fill mode at a frequency of 1-4 times per day, depending on loading conditions. Each operating condition was maintained long enough to reach steady state and to obtain sufficient data to characterize operation and performance.

Performance of the processes has been evaluated principally with conventional measures, including volatile and total solids (VS and TS), volatile fatty acids (VFA), gas production and composition, soluble and total COD, ammonia and total Kjeldahl nitrogen, pH, alkalinity, and fecal coliform and salmonella bacterial numbers. The results of the steady state tests conducted show stable performance at 12 day-12 day, 8 day-8 day, and 4 day-8 day operation.

Overall volatile solids reduction for the coupled thermophilic-mesophilic process averaged between 68 and 74 percent. This compares favorably with the 62 – 68 percent volatile solids reduction observed when the thermophilic and mesophilic digesters were operating independently, i.e. prior to coupling, and 64 – 78 percent removal in the WPTP full-scale

Digester 2. The thermophilic phase was responsible for approximately 80 percent of the VS destruction and gas production, with the mesophilic phase contributing about 20 percent.

KEYWORDS

Thermophilic, anaerobic, digestion

INTRODUCTION

The King County Department of Natural Resources Wastewater Treatment Division, Seattle, WA has been evaluating digestion enhancement technologies for implementation at the West Point Treatment Plant (WPTP). The primary objectives of the enhancement are improved volatile solids destruction and/or the ability to operate reliably at reduced hydraulic retention time due to projected increases in loads, and King County's desire to remove a digester to address public concerns.

Thermophilic digestion was selected as a treatment which has the potential to meet the primary objectives. Brown and Caldwell Consultants were retained by King County to perform an engineering evaluation and preliminary design to implement a thermophilic process at a demonstration scale. Evaluation tools included a literature review, plant surveys, and a workshop to define the thermophilic alternatives. The selected alternative was temperature phased anaerobic digestion with thermophilic followed by mesophilic. Details of the selection process are provided in a paper titled "Applicability of Thermophilic Anaerobic Digestion For the West Point Treatment Plant" presented at the 1998 WEF Annual Residuals and Biosolids Management Conference in Bellevue, WA (McCarthy, 1998).

One of the objectives of the pilot investigation was to evaluate the thermophilic-mesophilic process reliability and performance at loadings that were representative of full-scale implementation at the WPTP in the design year of 2029. Therefore, the first step in planning the pilot test was to conceptualize a full-scale thermophilic-mesophilic configuration at the WPTP. The WPTP has six existing 31-meter diameter, 8,290-cubic meter anaerobic digesters. Of these, one is retained as a digested sludge storage tank, and is not considered in the digestion capacity of the plant. Of the other five, King County is evaluating the feasibility of eliminating one tank in order to reclaim the area as beach for public access. Therefore, for the remaining four tanks, the thermophilic-mesophilic process would be configured as two tanks dedicated to thermophilic operation, followed by two tanks dedicated to mesophilic operation. Solids loading projections (including average, peak 3-week, peak week, peak 3-day, and peak day) for the design year of 2029 were then applied to this configuration to establish solids retention time (SRT) and volatile solids loading. Loadings were also established for maintenance conditions with one thermophilic digester out of service for cleaning. These projected full-scale loadings became the target loadings for operating the pilot scale thermophilic-mesophilic process (Brown and Caldwell, 1999) and (McCarthy, 1998).

This paper will discuss the pilot testing of the selected thermophilic digestion process at the WPTP.

METHODS AND MATERIALS

Digesters. Two stainless steel cylindrical tanks each having a capacity of 1,900-L were operated as anaerobic digesters. Each tank measured 137 cm in diameter with a sloped bottom and domed top. A top mounted pneumatically powered mixer equipped with a single two-bladed pitched 20-cm diameter impeller provided mixing energy. Tracer testing during the course of piloting confirmed adequate mixing. Tank temperatures were maintained at 55^{o} and 35^{o} C by a temperature controller, hot water reservoir, water circulator, and tank water jacket.
Each tank was equipped with two temperature probes in thermowells, a gas flowmeter (Kurz Model 502FT-6A insertion mass flow, Monterey, CA), and differential pressure liquid level measuring instrumentation (Delta Controls Model 552 and 562, Shreveport, LA).

Seeding. The pilot thermophilic digester was seeded with anaerobic, thermophilic digested sludge from the Tacoma Central Wastewater Treatment Plant. The Tacoma Central Plant operates a dual-digestion process with thermophilic, aerobic digestion (1.5d SRT) followed by thermophilic and mesophilic, anaerobic digestion (6d SRT) and (6d SRT), respectively (Brown and Caldwell, 1998). The sludge was delivered to the pilot facility at a temperature of 45 ^{o}C and a concentration of 1.8 %TS. The pilot mesophilic digester was seeded with mesophilic digested sludge from the West Point Treatment Plant. The West Point Plant operates with mesophilic, anaerobic digestion (25d SRT). The sludge was delivered to the pilot facility at a temperature of 30 ^{o}C and a concentration of 3.0 %TS.

Feed. The pilot digesters were fed the same sludge as the WPTP full-scale mesophilic digesters with the exception of primary scum which is periodically pumped only to WPTP full-scale digesters 1, 2, and 3. The sludge was a 60:40 primary/secondary blend thickened by gravity belt thickeners. Sludge concentration ranged from 5 to 6 %TS with a gravity belt thickener control setpoint of 6 % and an average polymer dose of 2 kg/tonne-active. All pilot feed was routed through a grinder (3.2-mm cutter spacing) before pumping to the digesters. The feed sludge was not pre-heated and was pumped to the pilot digesters in the temperature range of 15 – 20 ^{o}C.

Waste/feed operations. In addition to the digesters, the pilot process was equipped with a 375-L polypropylene grinder tank; a 950-L polypropylene digester feed tank, and two 110-L polypropylene digester effluent tanks. Each of the tanks was equipped with float switches for process control. Specifically, the float switches in the digester effluent tanks were used to set the waste volume for SRT control. Transfer of solids in the pilot process was accomplished using pneumatically operated diaphragm pumps.

The routine operation of the pilot digesters consisted of daily wasting and feeding. To ensure consistency, a step-by-step procedure was written to guide the operation. The majority of the procedural tasks (valve and pump control) were accomplished via a central switch panel. In addition, a control panel for the grinder pump was located on a wall adjacent to the switch panel. Digester waste volume was controlled by effluent tank float switch setting. Digester feeding volume was controlled by the installed digester liquid level instrumentation. Digester wasting was completed prior to digester feeding under all operating conditions. Under coupled

operation, the waste from the thermophilic digester was cooled to below 45 ^{o}C and then fed to the mesophilic digester. The daily waste and feed operation frequency was based on the specific testing conditions. For example, the digesters were fed once per day at the 20-day SRT and four times per day at the 4-day SRT.

Performance Test Conditions. A series of performance tests were outlined for the pilot process to simulate proposed full-scale operating conditions of the thermophilic process at the WPTP. The full-scale operating conditions assumed the removal of an existing digester from the WPTP with the remaining digesters configured as two thermophilic digesters followed by two mesophilic digesters. Table 1 shows the performance test operating conditions.

Table 1. WPTP thermophilic pilot test operating conditions

Test Series	Digester Configuration	Thermophilic Digester SRT (days)	Mesophilic Digester SRT (days)	Test Criteria
Startup	Thermo Meso	20	20	(Startup) digesters operated in parallel
1	Thermo – Meso	8	8	(Performance Test) "Baseline" coupled operation in design year
2	Thermo - Meso	4	8	(Performance Test) "Baseline" coupled operation with thermo digester out for service in design year
3	Thermo - Meso	5	5	(Shock Load) Peak Week condition in design year
4	Thermo - Meso	2.5	2.5	(Shock Load) Peak Day condition in design year
5	Thermo - Meso	8	8	(Performance Test) Return to stability after peaking conditions

Analyses. TS, VS, alkalinity, ammonia, total Kjeldahl nitrogen, total volatile fatty acid, and fecal coliform counts were determined according to the *Standard Methods for the Examination of Water and Wastewater* (APHA, 1995). Volatile fatty acid speciation analysis was also done by gas chromatography (Lepisto and Rintala, 1995). COD was determined using Hach Manganese III COD method (Hach Company, Loveland, CO). Salmonella counts were determined according to literature method (Kenner and Clark, 1974). PH was measured with a Fisher Scientific dual channel pH/ion meter, model AR25, and an Orion Sure-Flow pH electrode, model 81-72BN. Carbon dioxide was measured using a fyrite gas analyzer (Bacharach Inc., Pittsburgh, PA). Hydrogen sulfide was measured using a colorimeter tube (Sensidyne, 1999).

RESULTS

Digester startup. Pilot digester startup was initiated in July 1999. Both pilot digesters were initially filled with water and heated to their respective operating temperatures. Just before addition of seed sludge, the heated water was drained and the seed sludge added to the pre-heated digesters. For both digesters, the transfer process was completed within a two-hour period. The mesophilic and thermophilic digesters were each seeded to a volume of 1,500 L and operated in parallel at a 20-day SRT. Digester wasting and feeding was performed once per day. Digester loading averaged 2.35 kg VS/m^3-day over an operating period of 95 days. Thermophilic and mesophilic digester temperatures were maintained at 55 +/- 1 and 35 +/-1 ^oC, respectively. The WPTP full-scale mesophilic digester-2 loading averaged 1.99 kg VS/m^3-day, and temperature averaged 36.7 +/- 0.5 ^oC over the same 95 days. Steady-state pilot digester operating conditions are shown in Table 2 along with WPTP full-scale mesophilic digester-2 during the same period for comparison. The steady state operating period is defined as the period following three detention times of operation at the given loading condition.

Table 2. Steady-state conditions of pilot digesters operating in parallel at 20 day SRT

Digester	SRT (days)	VS-Reduced [a] (%)	pH	VFA (mg/L)	Alk (mg/L)	NH_3-N [b] (mg/L)	CO_2 (%)	H_2S (ppm)
pilot thermophilic	20	63.7 (2.7)	8.0 (0.1)	711 (332)	6,634 (204)	2,010 (56)	37 (2)	383 (76)
pilot mesophilic	20	65.0 (3.7)	7.5 (0.1)	258 (111)	6,464 (861)	1,897 (103)	38 (2)	270 (61)
WPTP Full-scale Digester # 2	25	70.5 (7.0)	7.5 (0.1)	50 (15)	7,060 (295)	-	38 (1)	175 (30)

( ) – standard deviation
a - calculation methods pilots = mass balance, full scale digester = Van Kleeck (USEPA, 1999)
b - total ammonia as nitrogen

In addition, five samples from each pilot digester were analyzed for fecal coliform and salmonella. The samples were collected throughout the period of operation. Mesophilic pilot digester fecal coliform results were all below the limits for Class B biosolids – 2 x 10^6 MPN/gTS (USEPA, 1999). Thermophilic pilot digester fecal coliform and salmonella results were all below the limits for Class A biosolids - 1,000 MPN/gTS and 3 MPN/4gTS, respectively (USEPA, 1999).

Digester coupling. The thermophilic and mesophilic digesters were coupled at the 20-day SRT and transitioned to a final operating condition of an 8-day SRT in both digesters. Coupling was initiated on 20-Oct-99 and completed on 8-Nov-99. The transition was completed by increasing the digester feed by five percent per day. Digester operating conditions during the transition are shown in Figure 1.

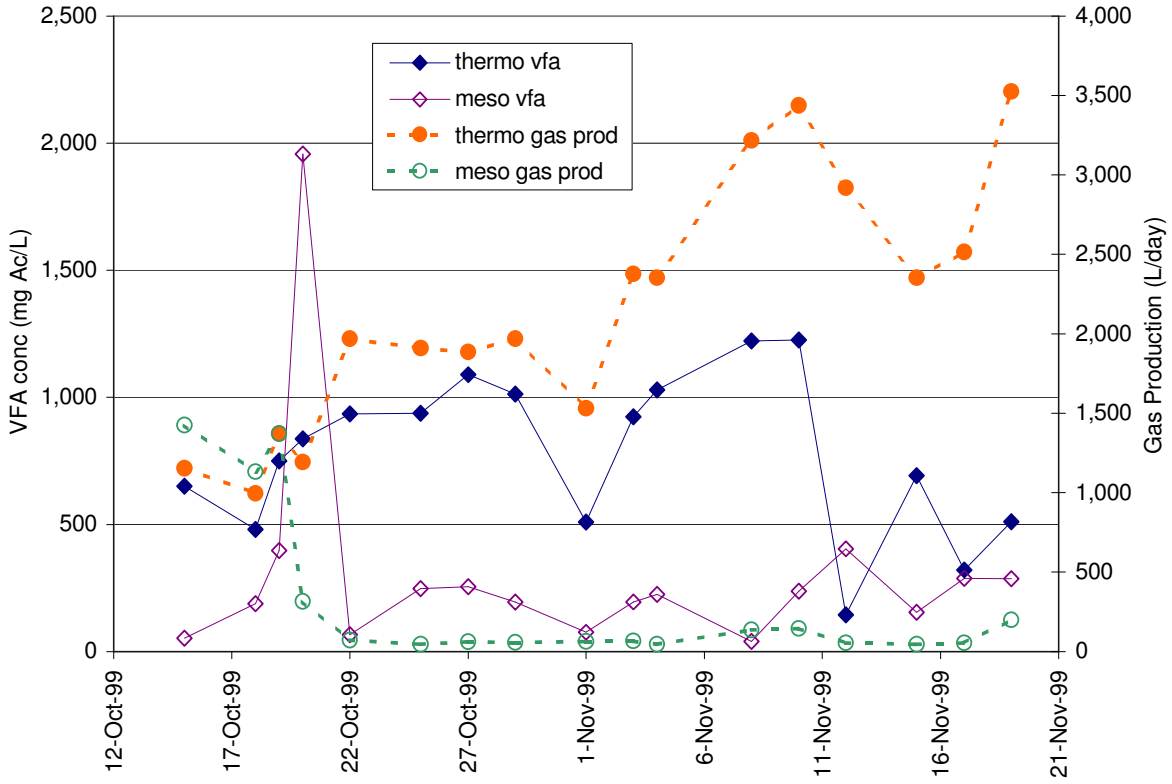

Figure 1. Pilot digester operating conditions during coupled transition to 8-day SRT

Test conditions. The coupled digestion process was operated under several SRT scenarios which were previously outlined in Table 1. The process was maintained at each condition for a minimum of three detention times (based on digester SRT). The transition of the process between operating conditions was completed by adjusting digester feed five percent per day. Data collection and sample analysis continued during each transition period. Digester volatile solids removal and volatile fatty acids under the various conditions are shown in Figure 2 and Figure 3.

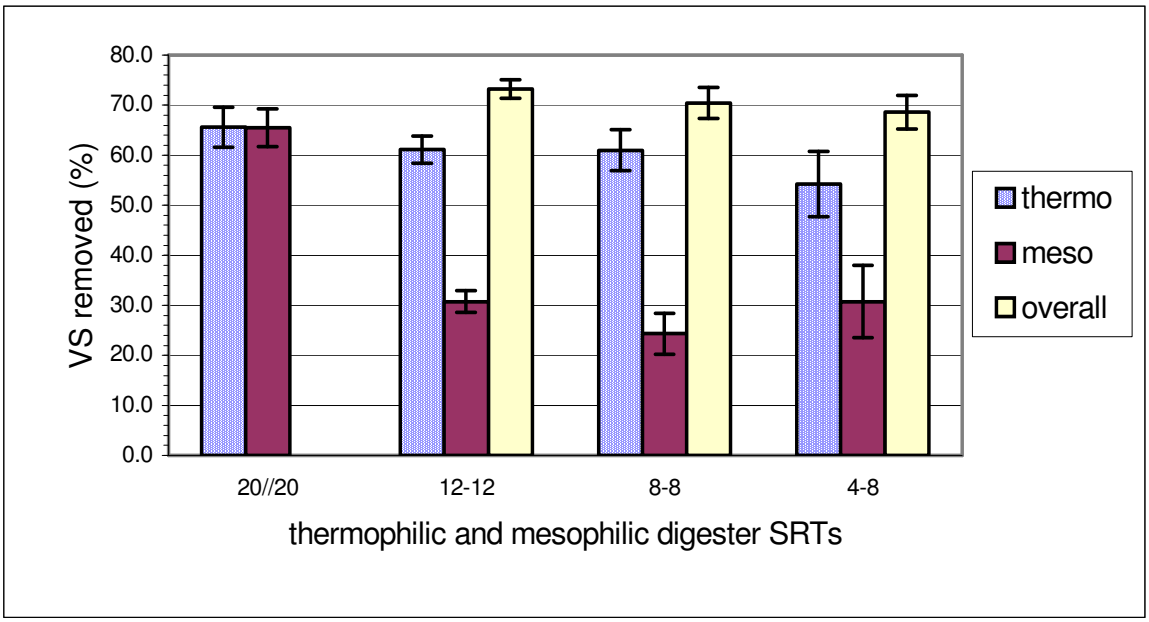

Figure 2. Percent of feed volatile solids destroyed for total system and in thermophilic and mesophilic digesters at each test condition.

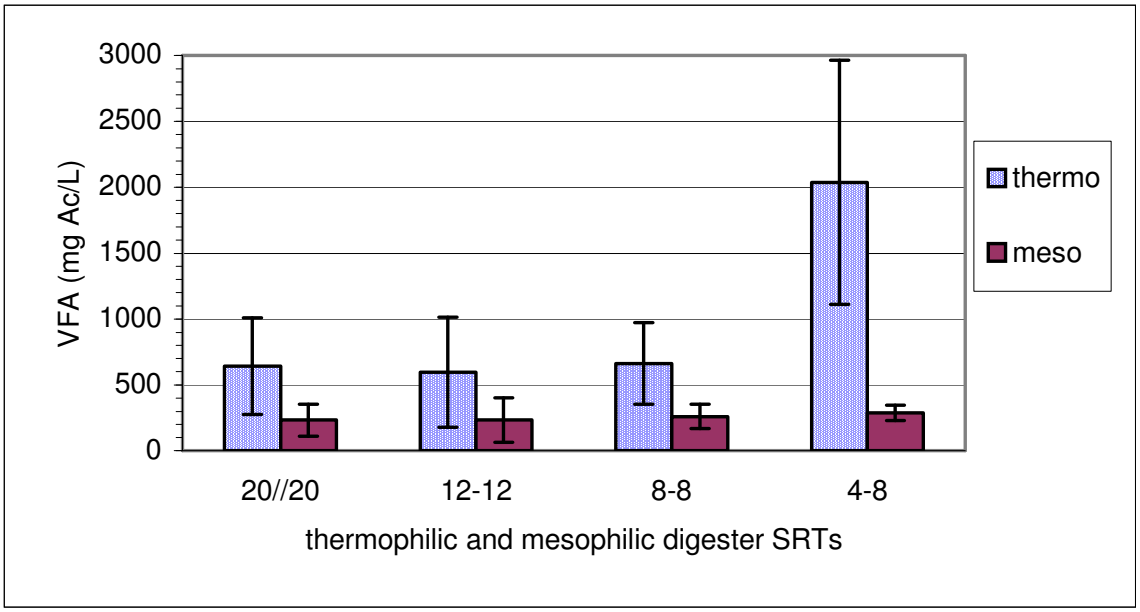

Figure 3. Total volatile fatty acid concentration in thermophilic and mesophilic digesters at each test condition.

Conventional operating data for the thermophilic and mesophilic digesters was collected during all operational phases and is shown in Table 3 and Table 4. Average thermophilic digester loading rates at 12 day, 8 day, and 4 day were 3.71 kg/m^3-day, 5.81 kg/m^3-day, and 11.78 kg/m^3-day, respectively. Average mesophilic digester loading rates at 12 day, 8 day, and 4 day were 1.29 kg/m^3-day, 2.26 kg/m^3-day, and 2.73 kg/m^3-day, respectively.

Table 3. Operational data for thermophilic digester at each test condition

	12d – 12d	data points	8d – 8d	data points	4d – 8d	data points
pH	7.8 (0.1)	10	7.8 (0.1)	44	7.6 (0.1)	11
Alkalinity (mg/L)	5,773 (350)	10	6,055 (329)	45	5,448 (262)	11
TCOD (mg/L)	32,156 (3,441)	9	35,700 (6,640)	42	44,673 (3,735)	11
SCOD (mg/L)	4,666 (1,203)	9	4,491 (893)	39	6,168 (1,951)	10
NH_3-N [a] (mg/L)	1,793 (105)	10	1,881 (285)	39	1,631	1
Gas Prod (L/g VS red)	0.71 (0.12)	9	0.58 (0.09)	42	0.63 (0.16)	11
CO_2 in gas (%)	42 (3)	10	41 (2)	47	39 (2)	10

( ) – standard deviation

a – total ammonia as nitrogen

Table 4. Operational data for mesophilic digester at each test condition

	12d – 12d	data points	8d – 8d	data points	4d – 8d	data points
pH	7.6 (0.1)	10	7.6 (0.1)	44	7.6 (0.1)	11
Alkalinity (mg/L)	6,304 (236)	10	6,750 (340)	45	6,787 (151)	11
TCOD (mg/L)	22,144 (2,228)	9	26,520 (3,673)	42	31,032 (3,972)	11
SCOD (mg/L)	2,299 (972)	9	2,673 (893)	39	2,807 (1,147)	11
NH_3-N [a] (mg/L)	1,775 (299)	10	2,056 (240)	39	1,995	1
Gas Prod (L/g VS red)	0.27 (0.06)	10	0.33 (0.11)	42	0.90 (0.29)	11
CO_2 in gas (%)	34 (1)	10	32 (2)	47	31 (1)	10

( ) – standard deviation
a – total ammonia as nitrogen

Over the course of testing, a total of thirteen samples from each pilot digester were analyzed for fecal coliform and salmonella. The samples were collected throughout the period of operation. Thermophilic and mesophilic pilot digester fecal coliform and salmonella results were all below the limits for Class A biosolids - 1,000 MPN/gTS and 3 MPN/4gTS, respectively (USEPA, 1999).

During the entire duration of coupled, pilot testing (Nov-99 to Sept-00), data continued to be collected from the WPTP full-scale mesophilic digester 2. Over the period, digester 2 SRT was 26 +/- 5 days and volatile solids reduction was 68 +/- 10 %. In addition, total volatile fatty acid concentration was 90 +/- 34 mg Ac/L.

During the 8 day- 8-day operational period, volatile fatty acid speciation was investigated as a stability measure. Volatile acid analysis using gas chromotography was completed and is shown in Figure 4.

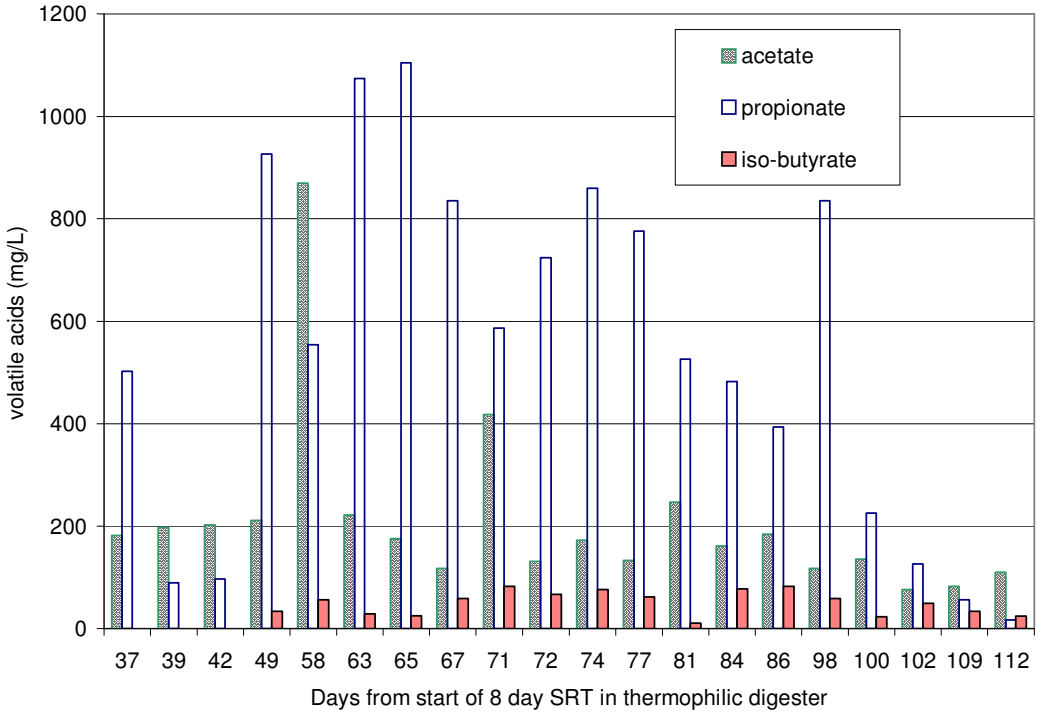

Figure 4. Volatile fatty acid concentrations in the thermophilic digester at sample days from start of 8d – 8d SRT operation

Peaking tests. Peak week and peak day digester operating conditions were simulated in the pilot process. Peak day was simulated in the middle of the peak week condition. WPTP full-scale operating data confirmed that the peak day occurred during the peak week. Digester wasting and feeding was increased to six events per day to minimize the digester temperature fluctuation due to unheated feed sludge. Average peak week loading on the thermophilic digester and mesophilic digester were 8.65 kg VS/m^3-day and 3.68 kgVS/m^3-day, respectively. Digester responses to the peaking conditions are shown in Figure 5.

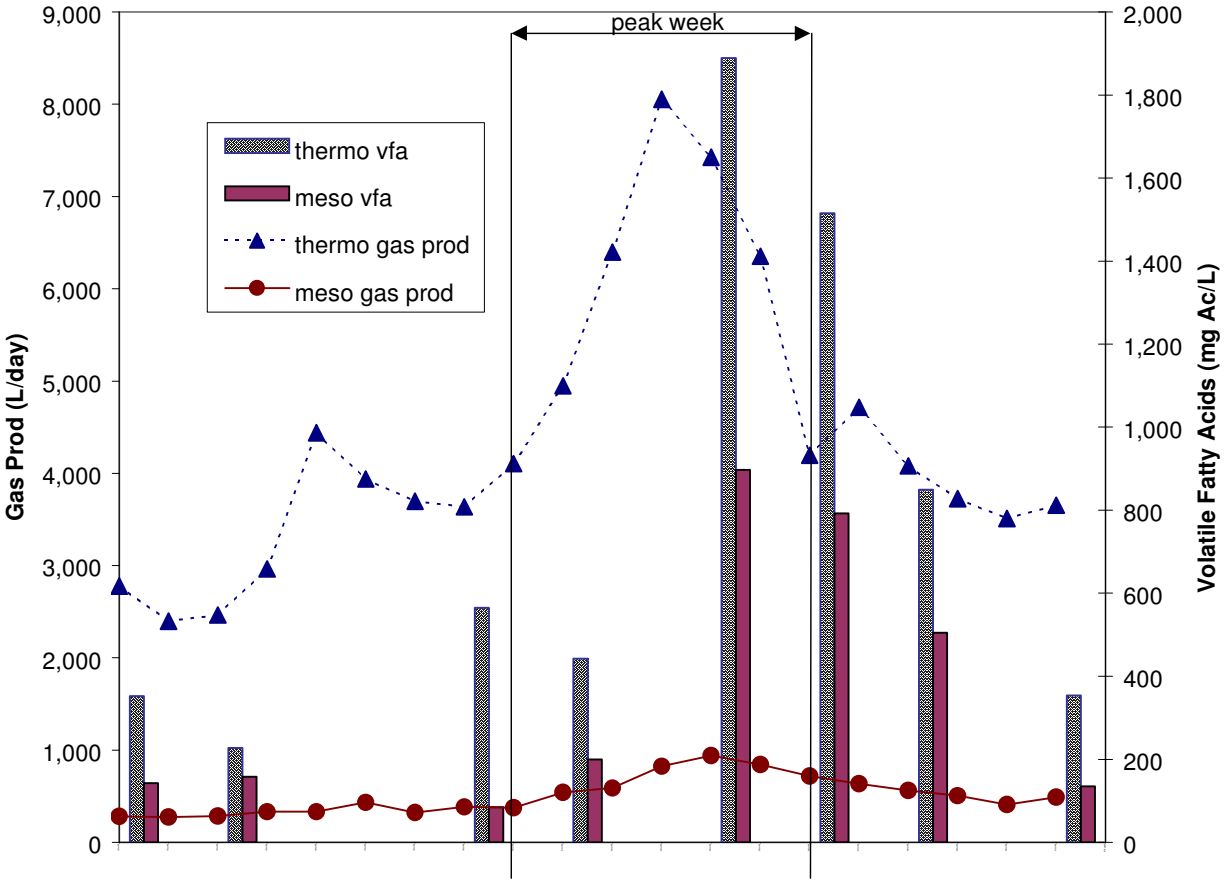

Figure 5. Operating digester response to peak week and peak day operating conditions

DISCUSSION

Startup. Initial operation of the digesters at the 20-day SRT provided an acclimation period and comparison of thermophilic and mesophilic digestion. Volatile solids reduction (VSR) was comparable with full-scale operation of digester 2 at the WPTP. Volatile fatty acid (VFA) levels were higher in both the pilot digesters than the full-scale digester.

Digester coupling. The thermophilic digester responded to the reduction in SRT with an increase in gas production and a temporary increase in VFA concentration. After coupling, the mesophilic digester gas production decreased and VFA levels increased. After reaching the 8-day– 8 day operating condition, both digesters continued to produce gas and VFA concentrations stabilized.

Test conditions. The operation of the process under several SRT conditions was intended to verify process stability. Stable operation was assessed by process response to the change in loading rates. Process response was primarily measured in terms of VSR and total VFA

concentration. Additional conventional parameters (gas production, alkalinity, pH, and carbon dioxide fraction in gas) were also used for process monitoring.

Under all test conditions, VSR was between 64 - 74 %. With a reduction in thermophilic digester SRT, VSR decreased in the thermophilic digester and increased in the mesophilic digester. The VSR increase in the mesophilic digester was expected with the increased loading of degradable intermediates from the thermophilic digester. Under the design year baseline operating condition of 8 day– 8 day, the thermophilic phase was responsible for approximately 80 percent of the VSR, with the mesophilic phase contributing about 20 percent.

The VSR in the coupled pilot digesters compares favorably with values documented in recent literature. Bench-scale digesters (7.4d thermophilic – 12.6d mesophilic) fed with 5.8 %TS primary/secondary reported an overall VSR of 55 % (Vandenburgh, 1999). In addition, VSR of a full-scale thermophilic-mesophilic process operated at a long process SRT reported a VSR of 68% (Streeter, 1997). Under all pilot conditions, VSR was comparable to reduction in the WPTP digester 2.

VSR standard deviation under all operating conditions was less than 10 %. Based on this operating parameter, the process exhibited stable operation at each of the loading conditions.

Total VFA analysis conducted during all test conditions was a primary tool for process monitoring. The VFA concentration in the thermophilic digester increased with a decrease in SRT while the mesophilic digester remained relatively constant. In addition, the thermophilic digester total VFA was widely variable under all operating conditions. The ability of the mesophilic digester to maintain low VFA concentrations (below 400 mg Ac/L) suggests that the overall process is capable of handling varied loading conditions with minimal impact to the final digested product.

The total VFA concentration in the coupled pilot digesters is comparable to values documented in a recent literature article. Bench-scale digesters (7.4d thermophilic – 12.6d mesophilic) fed with 5.8 %TS primary/secondary reported total VFA concentrations of 1,500 mg Ac/L and 400 mg Ac/L in the thermophilic and mesophilic stages, respectively (Vandenburgh, 1999).

In addition to total VFA concentration analysis, volatile acid speciation was performed for a period of time following digester coupling. Figure 4 shows that propionate was the predominate acid in the thermophilic digester during a large portion of the 8 day– 8 day operation. The predominance of propionate may indicate difficulties in the metabolic steps of anaerobic treatment (Speece, 1996). After approximately 100 days operation the proprionate concentrations dropped. This suggests that the thermophilic digester required several SRTs for biomass acclimation to the new loading conditions.

Results from pathogen testing showed that the coupled digesters were consistently below the limits set for Class A biosolids. The results are supported by literature stating that the temperature phased anaerobic process is superior to a single anaerobic mesophilic stage with respect to pathogen removal (Vik and Olsen, 1997 and Streeter, 1997).

The process was not affected by the effect of free ammonia, a known toxic species to anaerobic digestion (Speece, 1996), at an average concentration of 310 mg/L and 85 mg/L in the thermophilic and mesophilic digesters, respectively. These values are considerably higher than toxic threshold concentrations reported in literature for un-acclimated mesophilic and thermophilic sludge (Bhattacharya and Parkin, 1989).

Peaking tests. Digester response to peaking conditions, highlighted in Figure 5, shows the process is capable of handling the anticipated peak design loading conditions. Within one week, the total VFA concentration in each digester returned to its pretest level.

CONCLUSIONS

Anaerobic thermophilic-mesophilic digestion is capable of reliable operation at the projected solids loading to the West Point Treatment Plant in the design year 2029, even with loadings simulating the removal of one digester.

Stable digestion was achieved with digester operating conditions of 8-day solids retention times in both the thermophilic and mesophilic digesters (16-day SRT total).

Pilot process volatile solids reduction was comparable to volatile solids reduction observed in the WPTP mesophilic digestion process, even at significantly lower SRT.

Besides conventional parameters such as gas production, total volatile fatty acid concentration, and carbon dioxide fraction in digester gas, the pilot testing suggests the use of speciated volatile fatty acid concentrations as a process monitoring parameter.

The process successfully recovered from simulated treatment plant solids peaking conditions, with thermophilic and mesophilic SRT values as low as 2.5 days, respectively.

Results from this pilot study shows that anaerobic thermophilic-mesophilic digestion has the potential to meet Class A pathogen requirements for biosolids.

The digestion process did not appear to show the toxic effect of free ammonia at the observed test levels.

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