TEMPERATURE PHASED ANAEROBIC DIGESTION SYSTEM MONITORING PROJECT AT TINEDALE FARM

FINAL REPORT

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EXECUTIVE SUMMARY

Tinedale Farms LLP in Wrightstown, Wisconsin, is one of the largest dairy production operations in the state of Wisconsin, housing nearly 2,500 animals. These dairy cows produce approximately 50,000 gallons of manure per day, which also includes parlor water and other water used for cleanup. Tinedale Farms spent several years researching various anaerobic digestion technologies that were commercially available, with a stated goal of maximizing solids conversion to methane that can be used for the generation of renewable energy in the form of electricity of thermal energy. Based on this preliminary research, Tinedale Farms determined that a temperature-phased Anaerobic Digestion (TPAD) system was most likely to meet their short and long-term objectives. The TPAD system utilizes thermophilic temperatures in the first phase and mesophilic temperatures in the second phase. It should be noted that the TPAD system is patented and assigned to the Iowa State University Research Foundation, Inc.

The TPAD system at Tinedale Farm was constructed in 2001, attracting attention in Wisconsin and nationally, as it was the first TPAD system being operated by the dairy industry in the United States. Efforts to operate the system as a TPAD have been ongoing, with a second startup initiated in the spring of 2002 under the direction of Fox Engineering, after several equipment modifications had been completed to the system during late 2001 and early 2002. This report summarizes the various operating conditions that occurred during the second TPAD start-up.

Although the TPAD system has been used successfully at several municipal wastewater treatment facilities and laboratory studies have shown it to be effective on dairy manure, the TPAD system has not yet been successfully operated at Tinedale Farms. Several factors were thought to contribute to the inability to get the system to perform as a TPAD. These factors included ongoing equipment issues that did not allowed steady-state operation of the anaerobic digestion system (primarily related to ongoing operational issues with the two engine-generators), potential toxicity caused by high volatile fatty acid concentrations during startup of the thermophilic reactor, and the potential toxicity of other farm additives (antibiotics, chemicals for hoof treatments, etc.) on the thermophilic portion of the reactor. Given the ongoing difficulty of operating the anaerobic digester as a TPAD system, Tinedale Farms has converted the entire reactor back to mesophilic temperatures and will continue to operate the anaerobic digestion system as a complete-mix mesophilic system until more information can be gathered on the potential factors contributing to the failed attempt to operate the system successfully as a TPAD.

1.0 INTRODUCTION

The dairy industry contributes $10 billion annually to the economy of Wisconsin. Most of the 21,000 dairy farms in Wisconsin are small, with less than 150 head, and operate on relatively small margins of 3-5%. However, the current trend is toward greater numbers of livestock per farm site. It is estimated that there are already more than 100 farms in Wisconsin that have at least 1,000 animals, with many more being proposed or constructed. Non-farming citizens that object to farm odors from existing facilities may lodge complaints with their township or county, triggering re-assessment of regulations already in place and subsequent passage of more stringent and expensive regulations. Within the next several years, it is also likely that a new federal and state regulatory framework governing agricultural waste management will be instituted. Ideally, the industry response to the manure management challenge will be cost-effective, sustainable, and adaptable for implementation on both large and small Wisconsin Farms.

Tinedale Farms, LLP, in Wrightstown, Wisconsin, is one of the largest dairy production operations in the state of Wisconsin, housing nearly 2,500 animals. The dairy cows at Tinedale Farms produce approximately 50,000 gallons of manure per day with a solids content of 8-10%. Manure generated at the facility was historically discharged into a series of lagoons, with a capacity of 17 million gallons and later land-applied. Because of its relative proximity to the Village of Wrightstown and the increasing cost and difficulty of manure and odor management, Tinedale Farms began actively pursuing other manure management options, including anaerobic digestion. It should be noted that farms have used anaerobic digestion for many years, with varying success. However, farm based anaerobic digestion has typically been accomplished using low technology systems such as covered lagoons or plug flow digesters.

Tinedale Farms spent several years researching the various anaerobic digestion technologies that were commercially available, with a stated goal of maximizing solids conversion to methane that can be used for the generation of renewable energy in the form of electricity of thermal energy. Tinedale Farms determined that a temperature-phased Anaerobic Digestion (TPAD) system was most likely to meet their short and long-term objectives. It should be noted that the TPAD system is patented (U.S. Patent No. 5,746,919) and assigned to the Iowa State University Research Foundation, Inc. The TPAD system has been used effectively at several municipal wastewater treatment plants including Sturgeon Bay and Neenah-Menasha, Wisconsin and Iowa

City, Newton, and Waterloo, Iowa. The major benefits that have been attributed to the TPAD system at these facilities are increased biogas production and pathogen destruction, which is increasingly becoming another significant issue for the dairy industry.

1.1 Drivers for Anaerobic Digestion

Several factors are currently making anaerobic digestion a more attractive option for farmers in Wisconsin and across the United States. The most significant factors are described below:

- Large-scale farms – The size of the average farm has been increasing rapidly, with half of the large-scale farms in Wisconsin started during the last two years. Because of the capital costs associated with anaerobic digestion, it typically becomes more cost effective as the size of the farm increases or when several smaller farms can utilize a system implemented through a cooperative arrangement.

- Environmental issues – There has been a call by several environmental groups for increased environmental scrutiny of farming operations by Environmental Protection Agency (EPA) and the Wisconsin Department of Natural Resources (WDNR). This specifically includes manure storage and management, which has been associated with odor and contamination of groundwater and surface water. Increased environmental regulations are likely to result in increased costs for manure management, again making alternative options such as anaerobic digestion viable.

- Renewable energy – Utilities are actively seeking sources of renewable energy to meet renewable portfolio standards, which are being proposed and implemented at the federal and state levels. In addition, several Wisconsin utilities have instituted “green” pricing programs where customers pay a premium price for energy generated from renewable sources such as manure.

These were several of the factors that contributed to the decision by Tinedale Farm to construct an anaerobic digestion system.

1.2 The Anaerobic Digestion Process

Anaerobic digestion can be defined as the biological oxidation of organic matter by microbes in an environment in which there is no molecular oxygen. The organic matter is a food source for the microbes, which convert it into new cells, energy for their life processes, and gaseous end products, such as methane and carbon dioxide. Anaerobic digestion can occur at mesophilic (85-100° F) or thermophilic (120-135° F) conditions. The advantages of digestion at thermophilic temperatures include higher rates of degradation, and therefore, the use of a smaller reactor and a lower capital cost, faster solid-liquid separation, and better control of bacterial and viral pathogens. The major disadvantage is that more heat must be added to the system than is necessary for the operation of mesophilic systems, which can be a significant issue in climates such as that of Wisconsin. However, this was not an issue at Tinedale Farms, which had excess heat production even after the needs of the thermophilic process were met.

Biogas, one of the products of anaerobic digestion, is typically made up of 55 to 65% methane (CH_4), 35 to 45% carbon dioxide (CO_2), and traces of ammonia (NH_3) and hydrogen sulfide (H_2S). Pure methane is a highly combustible gas that has an approximate heating value of 994 BTU/ft^3. Biogas can be burned in boilers to produce hot water, in engines to power electrical generators, and in absorption coolers to produce refrigeration.

Biosolids, the other product of anaerobic digestion, can be thickened, dewatered, and dried for use as animal bedding or combined with other organic materials for use as a soil amendment. It should be noted that Tinedale Farm has been exploring these opportunities through the Fox River Valley Organics Recycling (FRVOR) project, which is under the direction of Dr. Leslie Cooperband and Phil Wells from the University of Wisconsin-Madison. This ongoing project is attempting to develop opportunities for the sale of value-added products from materials such as municipal biosolids, dairy manure, paunch manure, and other food wastes generated in the Fox River Valley.

2.0 TERMPERATURE-PHASED ANAEROBIC DIGESTION

Farm based anaerobic digestion has typically been accomplished using low technology systems such as covered lagoons or plug flow mesophilic digesters. As stated previously, the primary goal of Tinedale Farms was to maximize solids conversion to methane. Therefore, Tinedale Farms focused on developing and implementing an advanced anaerobic digestion system that is cost-effective, sustainable, and adaptable for implementation on both large and small Wisconsin Farms. In the United States, the TPAD process has been successfully applied to the stabilization of municipal wastewater sludges in many full-scale facilities and proven to be capable of producing Class A biosolids, while also producing more biogas than other anaerobic digestion systems. Full-scale installations of the TPAD process indicated that volatile solids destruction and biogas production were approximately 25% higher than with other anaerobic digestion processes (Vik and Olsen, "Full Scale Operation of Temperature Phased Anaerobic Digestion", *Proceedings of the Water Environment Federation 70th Annual Conference and* Exposition, 1997), which would result in increased revenue from the sale of electricity. Both of these factors were extremely important to Tinedale Farms when considering the type of anaerobic digestion system that would be constructed.

2.1 General TPAD System Description

As noted previously, the TPAD system is patented by Iowa State University. A brief summary of the patent claims as related to agricultural waste are summarized as follows:

1. Method of treating a waste stream, comprising steps of 1) feeding the waste stream into a thermophilic anaerobic reactor; 2) maintaining thermophilic anaerobic conditions of the waste stream in the thermophilic anaerobic reactor for a pre-determined hydraulic retention time to generate a first biogas effluent comprising method and a first liquid effluent; 3) feeding the first liquid effluent from the thermophilic anaerobic reactor into a mesophilic anaerobic reactor and; 4) maintaining mesophilic anaerobic reaction conditions of the waste stream in the mesophilic anaerobic reactor for a predetermined hydraulic retention time to generate a second biogas effluent comprising methane and a second liquid effluent.

2. The thermophilic reaction conditions include a reaction temperature ranging from about 45° C to 75° C, with a normal reaction temperature of about 56° C. The mesophilic reaction conditions include a reaction temperature ranging from about 20° C to 45° C, with a normal reaction temperature of about 35° C. The hydraulic retention time in the thermophilic reactor is up to about 10 days, and the hydraulic retention time in the mesophilic reactor is up to about 20 days.

It should be noted that this patent also applies to other waste streams including liquid waste, primary sludge, secondary sludge, and sludge formed from domestic solid waste. The patent is also structured to include the following types of anaerobic reactor designs; fully-packed columns with random-pack or modular media, hybrid columns including an unpacked blanket zone and a packed zone, and suspended growth systems.

2.2 Tinedale Farms TPAD System Description

As designed, the TPAD system at Tinedale Farms falls within this general range of parameters described in the previous section. Manure from the free-stall barns is collected using a dry scraping system and combined with parlor water. The manure flows by gravity to a continually mixed equalization basin that is located adjacent to the anaerobic digestion system. The manure is then pumped from the equalization basin through a heat exchanger to achieve thermophilic temperatures prior to entering the thermophilic phase of the TPAD system. It should be noted that the heat exchanger utilizes recovered heat from the water jackets of two engine-generators, which operate on the biogas produced from the TPAD system. The thermophilic reactor is completely mixed using two draft tube style mixers. The partially digested manure is then pumped from the thermophilic reactor through a cooling heat exchanger, which brings the temperature down to mesophilic temperatures, and into the mesophilic reactor. The mesophilic reactor, which consists of two equally sized compartments that are each completely mixed using two draft tube-style mixers. It should be noted that the manure flow from the first mesophilic tank to the second mesophilic tank through a hole in the common wall separating the two tanks, with this configuration used to prevent any significant short-circuiting in the system. The digested manure then flows out the TPAD system by gravity to the existing series of lagoons, or it can be pumped to the solids handling and water clarification processes.

2.3 Tinedale Farms TPAD System Controls

A customized computer program developed by Telemetry & Process Controls, Inc., of Stillwater, Minnesota, is utilized to control all aspects of the TPAD system at Tinedale Farm, including the following: pumps, mixers, the gas handling system, the water cooling loop, and it monitors the performance of the engine generators. The program also has alarm settings for the various system components and can notify the operator via a paging system of any operational issues. An additional module for the computer system, which has not yet been purchased, includes several other data evaluation tools and performance charting features.

3.0 PROJECT HISTORY

The anaerobic digestion system at Tinedale Farm was constructed in 2001. By June of 2001, the system was operating at mesophilic conditions. In September of 2001, as the anaerobic digestion system approached steady state, the temperature of the thermophilic reactor was increased to 55°C. However, due to issues associated with the cooling heat exchanger, the system could not be maintained at the two separate temperatures required for the thermophilic and mesophilic portions of the digester, 55°C and 35°C respectively. These complications resulted in a temporary shutdown of the anaerobic digester. After corrections were made to the cooling heat exchanger, a second start up of the anaerobic digester was initiated in early 2002. A general description of the events from the second anaerobic digester startup, which is separated into five distinct periods, is listed in Table 1.

Table 1. DIGESTER OPERATIONS FOLLOWING THE SECOND START-UP

DATE	OPERATING CONDITION
PERIOD 1	
February 5-26, 2002	Recirculation of anaerobic digestion system
February 12, 2002	Approximately 24,000 gallons of biosolids from the City of Appleton Municipal Wastewater Treatment Plant were used to seed the anaerobic digester.
February 27, 2002	Gas production increased enough to run one generator, raw manure was fed to the anaerobic digestion system.
March 9, 2002	Feed rate for raw manure was increased to 60% of load (95 L/min or 25 gal/min).
March 15, 2002	Feed rate for raw manure was increased to 100% of load (125 L/min or 33 gal/min).
March 21, 2002	Feed rate for raw manure was decreased back to 91 L/min (24 gal/min).
April, 2002	Feed rate for raw manure was slowly increased back to 100% of load (125 L/min or 33 gal/min).
May-June, 2002	Feed rate for raw manure was maintained at 100% of load (125 L/min or 33 gal/min).
June 26, 2002	Both generators fail due to mechanical problems.
July, 2002	Feed rate for raw manure was maintained at 132 L/min (35 gal/min).
August 1-August 28, 2002	Feed rate for raw manure was maintained at 117 L/min (31gal/min).
PERIOD 2	
August 29-September 4, 2002	Shutdown of raw manure feed (0 L/min), Began recycling mesophilic effluent back to the mesophilic tank at 152 L/min (40 gal/min).

September 4-September 16, 2002	Feed rate for raw manure was maintained at 75 L/min (20 gal/min). Mesophilic recycling rate was reduced to 75 L/min or (20 gal/min) for 12 hrs/day.
September 17-October 1, 2002	Feed rate of raw manure was increased to 95 L/min (20 gal/min), mesophilic recycling rate varied as one generator was brought back on line.
October 9, 2002	Generator brought on-line and producing power.
PERIOD 3	
October 21, 2002	Began heating thermophilic reactor. All feeding into the digester was stopped.
October 25, 2002	Initiated batch feed of raw manure into the mesophilic reactor. Recycled mesophilic effluent was also fed to the thermophilic reactor.
October 29, 2002	Generator was taken off-line due to limited biogas production. Thermophilic reactor was stable at 55°C.
November 25, 2002	One generator was brought back on-line. Heat was being recovered to heat thermophilic influent, but not enough biogas was available to produce power for distribution.
December 10, 2002	Began constant feeding in the mesophilic portion at 45 L/min (12 gal/min), with recycled mesophilic effluent still being batch fed to the thermophilic reactor.
PERIOD 4	
January 6, 2003	Stopped feeding into the thermophilic reactor, which was now operating as a batch reactor. Raw manure feed into the mesophilic reactor was maintained at 45 L/min (12 gal/min)
January 14, 2003	Feed to the mesophilic reactor increased to 57 L/min (15 gal/min).
January 22, 2003	Feed to the mesophilic reactor was reduced to 45 L/min (12 gal/min) due to concerns with high VFA concentrations.
February 13, 2003	Feed to the mesophilic reactor was increased to 49 L/min (13 gal/min), no feeding into the thermophilic reactor.
March 8, 2003	Feed to the mesophilic reactor was increased to 53 L/min (14 gal/min), no feeding into the thermophilic reactor.
March 11, 2003	Feed to the mesophilic portion was increased to 57 L/min (15 gal/min), no feeding into the thermophilic reactor.
PERIOD 5	
April 9, 2003	Began wasting 50% of the thermophilic effluent.
April 15, 2003	Wasting of thermophilic effluent completed. Thermophilic reactor refilled with mesophilic effluent.
April 23, 2003	Refilling of thermophilic reactor completed, feeding 57 L/min (15 gal/min) of raw manure into the mesophilic reactor, feeding to thermophilic reactor stopped.
May 7, 2003	Feed to the mesophilic reactor increased to 61 L/min (16 gal/min), recycling 53,000 L/day (14,000 gal/day) of mesophilic effluent into the thermophilic reactor.

May 20, 2003	Feed to the mesophilic reactor reduced to 51 L/min (13.5 gal/min), feeding 19 L/min (5 gal/min) of raw manure to the thermophilic reactor.
June 3, 2003	Feed to mesophilic reactor increased to 68 L/min (18 gal/min), reduced raw manure feeding to the thermophilic reactor to 10 L/min (2.5 gal/min).
June 19, 2003	Feed to mesophilic reactor returned to 51 L/min (13.5 gal/min), raw manure feeding to the thermophilic reactor returned to 19 L/min (5 gal/min).
July 1, 2003	The thermophilic process was halted. The temperature in the thermophilic reactor is reduced to mesophilic temperatures and the entire digester will be operated as a complete-mix mesophilic system.

The performance of the anaerobic digestion system at Tinedale Farms during the second startup will be analyzed in this report. Section 4 will describe the characteristics of the manure from the primary operations of the anaerobic digestion system, including the following: raw manure influent, thermophilic reactor effluent, and mesophilic reactor effluent. Section 5 will describe the anaerobic digestion system performance during the five separate operating periods described in Table 1, with detailed data on the manure characteristics and system performance during each period.

4.0 SYSTEM OPERATING DATA

Graduate students from the Environmental Science and Policy program at the University of Wisconsin-Green Bay monitored the anaerobic digestion system at Tinedale Farm since June of 2001. Laboratory testing has provided significant amounts of data that can be used evaluate the overall performance of the anaerobic digestion system, as operated as a TPAD system or operating under entirely mesophilic temperatures. Liquid samples were typically collected at three sample points, consisting of the following:

- Raw manure
- Thermophilic reactor effluent
- Mesophilic reactor effluent

Manure samples were monitored for the following characteristics:

- Flow rate
- pH
- Temperature
- Alkalinity
- Solids (total, volatile and fixed)
- Chemical Oxygen Demand (total and soluble)
- Volatile fatty acids
- Pathogens (were to be done periodically after conversion to TPAD)

Biogas from the system was also collected at two sample points, consisting of the following:

- System biogas
- System biogas after gas cleaning

Biogas was monitored for the following characteristics:

- Flow rate
- Composition (methane, carbon dioxide and hydrogen sulfide)

4.1 RAW MANURE CHARACTERISTICS

The raw manure entering the anaerobic digestion system at Tinedale Farms is a combination of manure and cleaning/flush water from the parlor. A mechanical cleaning system scrapes the raw manure in the alleys of the barns to a central gutter. The manure then flows by gravity through the gutter to an equalization tank where it can either be pumped to the anaerobic digestion system or to a solids separation system. The characteristics of the raw manure influent, which represent averages from February 5, 2002 through June 30, 2003, are summarized in Table 2.

Table 2 – Raw Manure Influent Characteristics

Parameter	Units	Average	Standard Deviation
Flow Rate	GPD	32,300[1]	14,900
PH		7.58	0.44
Temperature	°C	16	5
Alkalinity	mg/L as $CaCO_3$	7700	1200
Total Solids	%	7.60	1.43
Volatile Solids	%	6.22	1.15
Fixed Solids	%	1.38	0.28
Chemical Oxygen Demand (COD)	mg/L	153,100	29,700
Soluble Chemical Oxygen Demand (SCOD)	mg/L	44,000	10,800
Volatile Fatty Acids (VFA)	mg/L	2800	1200

[1] Only represents manure fed to the anaerobic digestion system. Average flow rate is approximately 50,000 gallons per day.

The data in Table 2 indicates that there is some variability in the raw manure characteristics, most notably with the solids and the COD. Many factors influence these characteristics, with some of the variation attributed to seasonal changes in animal feed, evaporative losses, and the use of sprinklers/misters in the barns during warm weather. Total solids concentrations typically range from 2% in flush barn cleaning systems to 15% in scraper or dry cleaning systems. Because of the combination of the scraped manure and parlor water at Tinedale Farms, the total solids concentration averaged 7.60%. It can also be seen in Table 2 that the volatile solids are approximately 80% of the total solids found in the manure. Volatile solids are the solids component reduced by bacteria during anaerobic digestion and are therefore an extremely important measurement. The COD and SCOD are also important, as the COD and SCOD are indicators of the available food for the anaerobic bacteria within the digester. Over the course of the anaerobic digestion system monitoring, the COD in the raw manure averaged 153,000 mg/L, with the SCOD averaging 44,000 mg/L. The pH of the raw manure stayed fairly constant throughout the course of monitoring, averaging 7.58. Alkalinity, a measure of the ability to buffer or resist changes in Ph upon the addition of an acid, varied considerably throughout the study. Alkalinity averaged 7700 mg/L as $CaCO_{3,}$ but concentrations were found to be highly dependent on solids concentration, as lower solids concentrations were often the result of increased water use for animal comfort during warmer temperatures or inflow from storm events. A final parameter, volatile fatty acids (VFAs), was very important in monitoring the performance of the anaerobic digestion system. The VFAs are an intermediate product of the anaerobic digestion process, signifying anaerobic activity by acid forming bacteria and more significantly are an indication of poor performance by propionate-utilizing acetogens and acetate utilizing methanogens. It should be noted that the VFA concentrations of the raw manure influent were also found to have seasonal variations. Throughout the monitoring period the VFAs averaged 2800 mg/L, but variations observed suggest that anaerobic activity in the raw manure before entering the digester increases during the warmer months. Further detail in the trends of different raw manure characteristics for each study period will be discussed in Section 5.0 of the report.

4.2 THERMOPHILIC EFFLUENT CHARACTERISTICS

As noted previously, the anaerobic digestion system did not operate at thermophilic temperatures during the entire length of this research. The TPAD startup protocol called for the initiation of the thermophilic process after the digester had stabilized under mesophilic conditions, which was determined to occur in October of 2002. A summary of the thermophilic effluent characteristics can be seen in Table 3.

Table 3 – Thermophilic Effluent Characteristics

October 21, 2002 – June 30, 2003

Parameter	Units	Average	Standard Deviation
PH		7.88	0.23
Temperature	°C	54	4
Alkalinity	mg/L as $CaCO_3$	11,300	800
Total Solids	%	5.95	0.99
Volatile Solids	%	4.50	0.80
Fixed Solids	%	1.45	0.19
Chemical Oxygen Demand (COD)	mg/L	153,000	26,000
Soluble Chemical Oxygen Demand (SCOD)	mg/L	61,000	12,000
Volatile Fatty Acids	mg/L	6,000	1,700

It can be seen in Table 3 that the temperature in the thermophilic reactor averaged 54°C. However, the average temperature calculation includes a brief time when the thermophilic reactor was being increased to 55°C. Once the thermophilic portion was successfully brought to 55°C, the temperature stabilized and remained fairly constant at 55°C for the remainder of the monitoring period. It can be seen when comparing Table 3 to Table 2 that the pH and alkalinity in the thermophilic reactor were slightly higher than that of the raw manure. It can also be seen that the total solids and volatile solids were lower after the first phase of anaerobic digestion. However, this lower solids concentration is a result of several factors, including the recycling of mesophilic effluent into the thermophilic reactor. Mesophilic effluent was fed into the digester due to the higher than desired VFA concentrations found in the thermophilic reactor. The mesophilic feedstock was intended to act as seed for the thermophilic bacteria and reduce the high VFA levels through dilution. The VFAs averaged 6000 mg/L but the target value in the protocol was a maximum of 3000 mg/L. The main concern with high VFA concentrations is a decrease in pH due to excessive acid concentrations, creating a toxic environment for the bacteria. The high alkalinity of the manure reduces this danger somewhat by stabilizing the pH as mentioned above. A comparison of the COD in Table 3 and Table 2 shows nearly identical values of 153,000 and 153,100 mg/L respectively. This indicates that minimal organic matter was being utilized in the thermophilic reactor, which was also evident because of low biogas production of the system.

4.3 Mesophilic Effluent Characteristics

During the entire monitoring period, approximately two thirds of the anaerobic digester volume was operated at mesophilic temperatures. A summary of the mesophilic effluent characteristics can be seen in Table 4.

Table 4 – Mesophilic Effluent Characteristics

Parameter	Units	Average	Standard Deviation
PH		7.76	0.12
Temperature	°C	36	3
Alkalinity	mg/L as $CaCO_3$	11,800	800
Total Solids	%	5.48	0.81
Volatile Solids	%	4.16	0.69
Fixed Solids	%	1.32	0.12
Chemical Oxygen Demand (COD)	mg/L	113,000	27,000
Soluble Chemical Oxygen Demand (SCOD)	mg/L	36,000	8500
Volatile Fatty Acids	mg/L	1300	1100

It can be seen in Table 4 that the temperature of the mesophilic reactor was maintained at a temperature of 36° C. It can be seen when comparing Table 4 to Table 3 that there is very little change in the pH, alkalinity, and solids characteristics of the thermophilic and mesophilic reactors. Much of this may be attributed to the mesophilic effluent being recycled to the thermophilic portion of the digester during much of the monitoring period. A comparison of the COD and VFA concentrations entering the mesophilic digester from Table 2 to the mesophilic effluent in Table 4 shows that the COD concentration in the mesophilic reactor was reduced to an average of 113,000 mg/L, more than a 25% reduction from Table 2. Average volatile solids in the raw manure was 6.22% as shown in Table 2, but the volatile solids in the mesophilic effluent was 4.16% as shown in Table 4. This is an overall volatile solids destruction rate of approximately 33%, which would likely have been higher without the numerous changes made in the overall operation of the entire anaerobic digestion system.

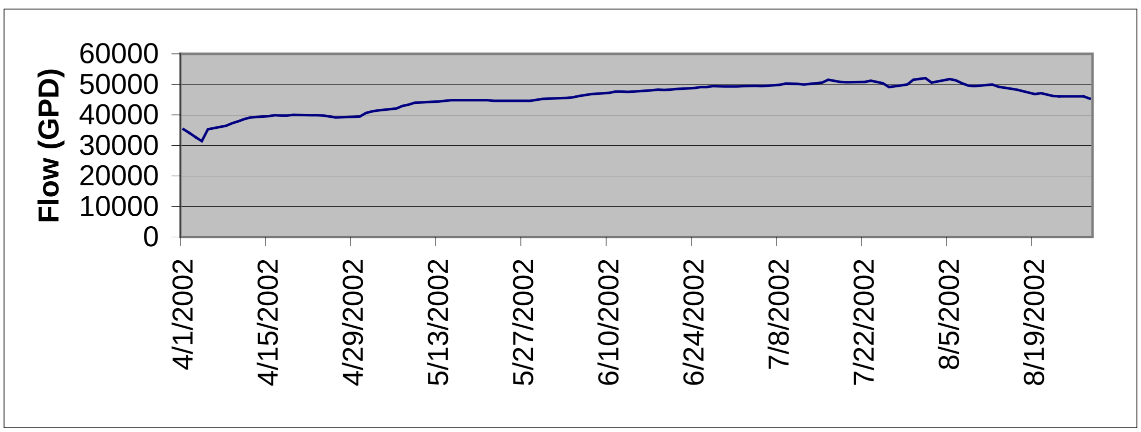
5.0 SYSTEM PERFORMANCE BY OPERATING PERIOD

As described in Table 1, five distinct operating periods occurred during this research project. This section will attempt to summarize the overall performance of the anaerobic digestion system during each of these periods. It should be noted that the data presented in all the graphs in this report represent 15-day moving averages, which more clearly shows changes in performance.

5.1 OPERATING PERIOD 1- MESOPHILIC START-UP

The first operating period started on February 5, 2002, when recirculation of the entire anaerobic digestion system was initiated. After several days of recirculation, the anaerobic digestion system was seeded with mesophilic effluent obtained from the City of Appleton Municipal Wastewater Treatment Plant. Based on the TPAD start-up protocol, the anaerobic digester was to be stabilized at mesophilic temperatures in preparation for bringing the thermophilic reactor up to thermophilic temperatures. The discussion of the data from this operating period will focus on April 1, 2002, through August 28, 2002. Figure 1 reports the flow rate of the raw manure.

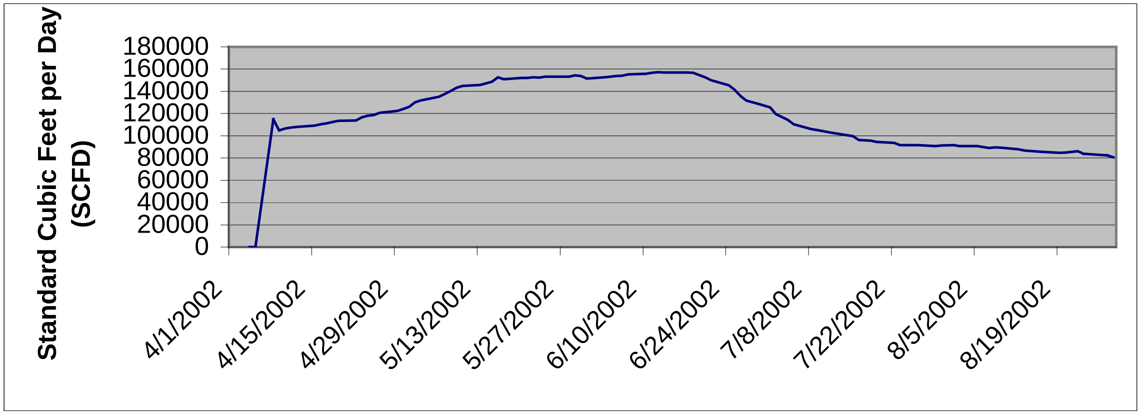
FIGURE 1 –RAW MANURE FLOW RATE
(April 1 – Aug 28, 2002)



It can be seen in Figure 1 that the raw manure flow rates were slowly increased during April and May. It should be noted that the increase in raw manure flow rate for June, July and early August could likely be attributed to the use of the misters in the barns to keep the cows cool. It should also be noted that a significant rain event occurred during early June, which was not entirely accounted for in Figure 1, adding a significant amount of excess water to the anaerobic digestion system through a flume pipe, which has since been modified to minimize this issue.

The biogas generation from the anaerobic digestion system at Tinedale Farm is monitored using a series of flow meters paid for, in part, from a grant from the Energy Center of Wisconsin. These flow meters measure the total amount of biogas generated as well any biogas that bypasses the engine-generators and sent to the flare. Figure 2 shows the biogas generation of the anaerobic digestion system during this period of operation.

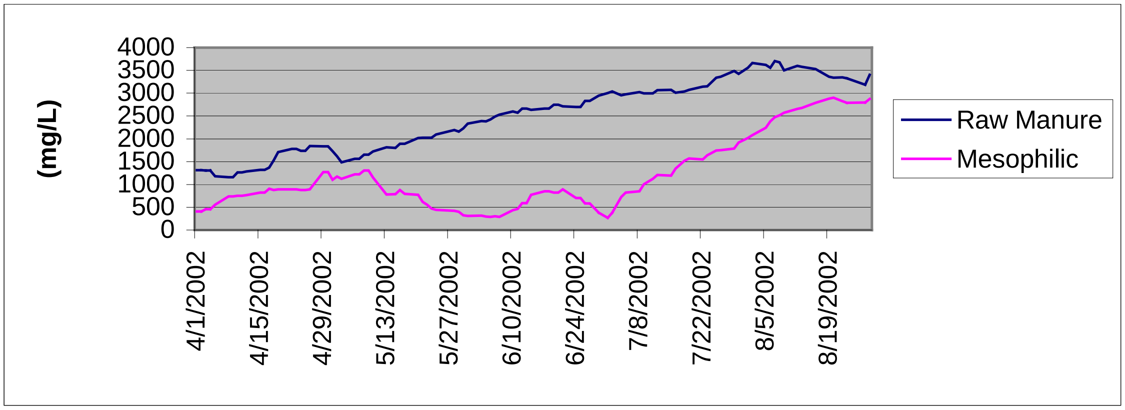
FIGURE 2 – BIOGAS GENERATION
(April 1 – Aug 28, 2002)



It can be seen in Figure 2 that the biogas flow rate was steadily increasing during the months of April and May, before it somewhat leveled off in June. At this point, the biogas generation from the anaerobic digestion system, which was being operated entirely at mesophilic temperatures, was great enough to operate one 375 kW engine-generator at capacity, with some additional biogas also being available for the second engine-generator. However, toward the end of June it can be seen in Figure 2 that a significant decrease in biogas generation occurred. A comparison with Figure 1 shows that the raw manure flow rates remained at 40,000 gallons per day during the month of April, which because of the lag time in the system from the long detention times, corresponds to the May biogas production. This same comparison can be made to the decreased biogas production in July and the increase raw manure flow rate in June, coupled with the excess water from the rain event. Based on these observations, it appears as though the increase in manure flow rate resulted in a decrease in detention time, which had a significant negative impact on biogas generation. Overfeeding a digester, particularly during start-up, can wash the desirable bacteria from the system quicker than they can reproduce, resulting in a poorly performing system.

Figure 3 shows the volatile fatty acid concentrations in the digester at the various sampling points.

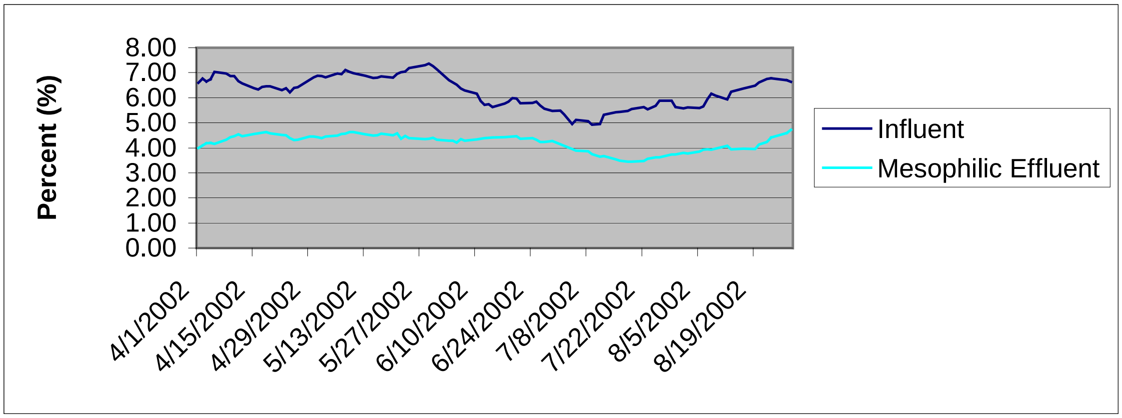
FIGURE 3 – VOLATILE FATTY ACID CONCENTRATION
(April 1 – Aug 28, 2002)



The large increase in the VFAs for the mesophilic effluent seen in Figure 3 during July and August is consistent with the poor biogas production that was observed during these periods. Methanogens, the methane-producing bacteria, have the slowest growth rate and are therefore the most susceptible to a decrease in detention time caused by an increase in the raw manure flow rate, similar to what occurred in June. A reduction in this group of bacteria is signaled by a reduction in biogas production and increased VFA concentrations. Therefore, this indicates that the VFAs were not being converted to biogas and were instead exiting the digester with the effluent, as the VFA concentrations for the mesophilic effluent shown in Figure 3 are opposite of the biogas trend in Figure 2. It can also be seen in Figure 3 that the VFA concentrations of the raw manure begin to increase as the ambient temperature increases, signifying an increase in anaerobic activity prior to the raw manure entering the anaerobic digestion system.

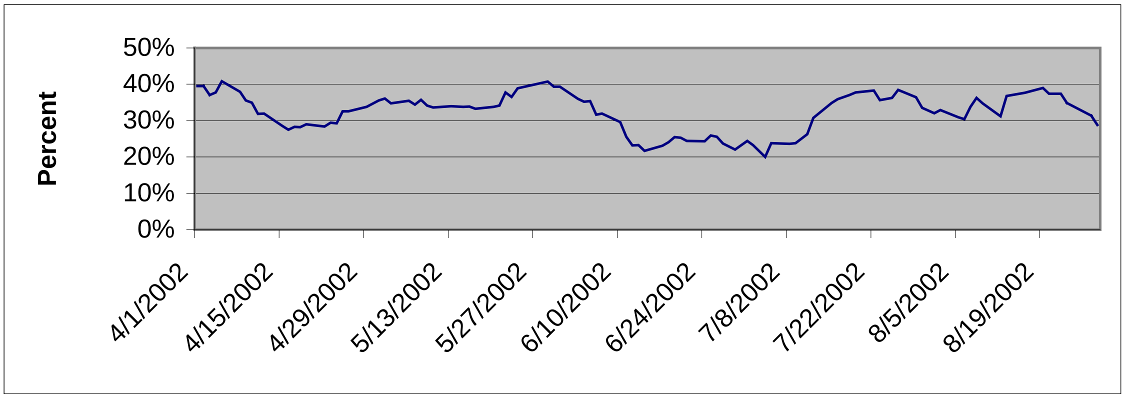
Figure 4 shows the volatile solids characteristics of the digester. It can be seen in Figure 4 that the volatile solids concentration in the raw manure influent began to decrease early in June, which corresponds to the increasing temperatures of the summer months and the use of the misters in the barns to cool the cows. It can also be seen in Figure 4 that the mesophilic effluent volatile solids consistently stayed near 4%, but also dropped in July reflecting the more dilute influent caused by the use of the misters.

FIGURE 4 – VOLATILE SOLIDS
(April 21 – Aug 28, 2002)



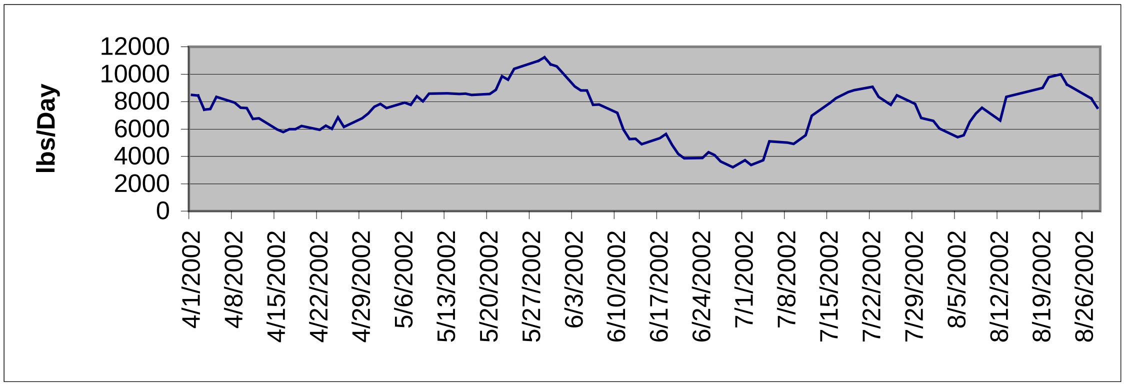
Volatile solids destruction is a measure of the overall reduction in the amount of organic material within the system, which corresponds closely with the amount of biogas generated. Figures 5 and Figure 6 show the volatile solids destruction as a percentage and the volatile solids destruction in pounds per day, respectively.

FIGURE 5 - VOLATILE SOLIDS DESTRUCTION BY PERCENT
(April 1 – Aug 28, 2002)



For the purposes of this study, a steady-state analysis was used to the determine the volatile solids destruction, i.e., the volatile solids destruction is determined by taking the total volatile solids entering the system less the total solids exiting the system divided by the total solids entering the system. Alternatively, a non-steady state analysis could be utilized, which would

FIGURE 6 - VOLATILE SOLIDS DESTRUCTION BY POUNDS PER DAY
(April 1 – Aug 28, 2002)

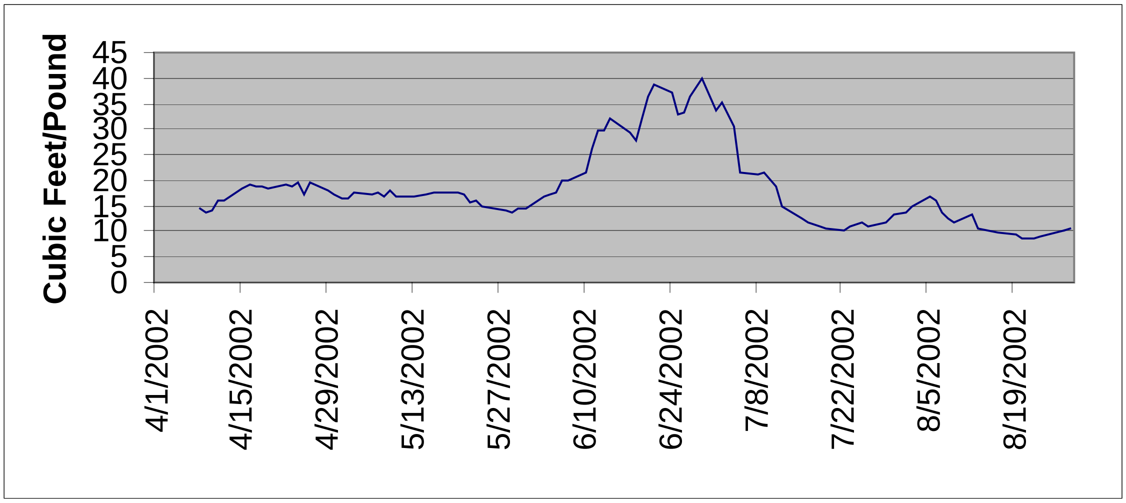


look at the average daily destruction based on the total amount of volatile solids destroyed divided by the number of days in the period, thereby providing an estimate of the total pounds of volatile solids destroyed over the length of the study.

It can be seen in Figure 5 that the volatile solids destruction approached 40 percent near the end of May, but then began to decrease during June. This is in some regard a reflection of the lower volatile solids percentage of the raw manure entering the system, which is the basis for the calculation of volatile solids destruction using a steady state analysis. Similarly, an increase in volatile solids destruction would be expected when the misters are stopped and the volatile solids content of the raw manure increases. Figure 6 shows a similar trend in the pounds of volatile solids destruction. The typical range of biogas generation versus volatile solids destruction for municipal wastewater application is 12-18 cubic feet per pound of volatile solids destroyed, with values on the lower end of the range being more applicable to manure. Figure 7 is a comparison of pounds of volatile solids destruction to the biogas generation.

It can be seen in Figure 7 that for the first half of the operating period the anaerobic digestion system produced approximately 15-17 cubic feet of biogas per pound of volatile solids destruction, which would be in the typical range of municipal wastewater treatment plants, but somewhat on the high side for manure. It can again be seen that changes to the anaerobic digestion system occurred in early June, once again attributed to the increased flow caused by

FIGURE 7 – BIOGAS VERSUS VOLATILE SOLIDS DESTRUCTION
(April 1 – Aug 21, 2002)



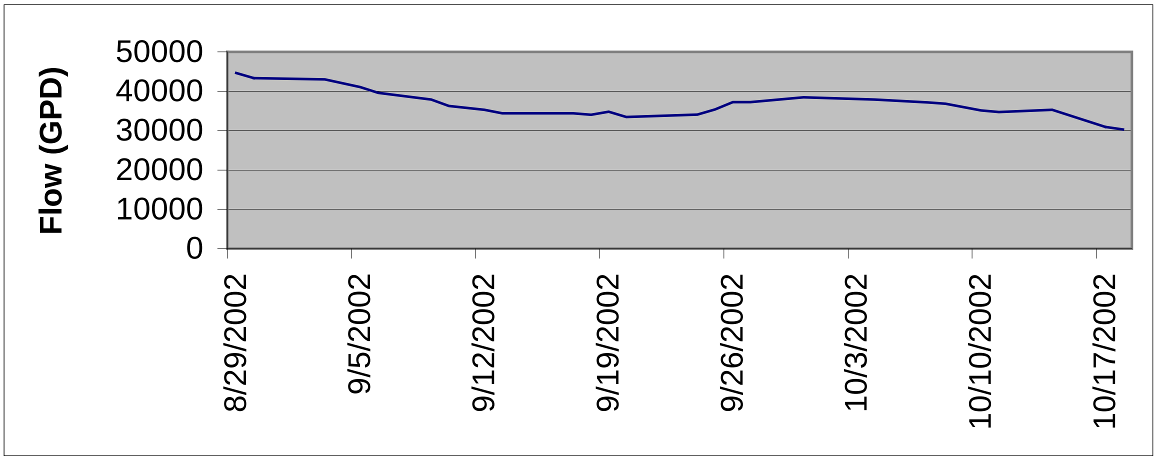
the use of the misters in the barns and a rain event. As shown in Figure 6, the pounds of volatile solids destroyed decreased in June. This results in an increase in the amount of biogas generated per pound of volatile solids destruction because the denominator (pounds of volatile solids destroyed) has been reduced when using the steady state analysis. Toward the end of July and early August, the ratio decreases again as the system stabilizes. However, it can be seen that the ratio from that period was lower than the 15-17 cubic feet of biogas per pound of volatile solids destruction prior to June and is closer to typical values for manure. It should also be noted that during this first operating period, the operation of both engine-generators was stopped on June 26, 2002, due to mechanical issues. As shown in Table 1, the engine-generators were brought back into on October 9, 2002. During the period when the engine-generators were not operational, natural gas was used for digester heating.

5.2 OPERATING PERIOD 2- MESOPHILIC REBUILDING

During the second operating period, August 29 to October 20, 2002, an effort was made to improve the health of the anaerobic digestion system. The issues detailed in the previous section reduced the performance and efficiency of the system causing anaerobic activity to decrease and almost fail. Flow into the digester was greatly reduced to increase residence time and to reduce VFAs that had begun to build up in the system. The increasing VFA concentration was a concern because VFA concentrations can cause toxicity issues and result in complete digester failure.

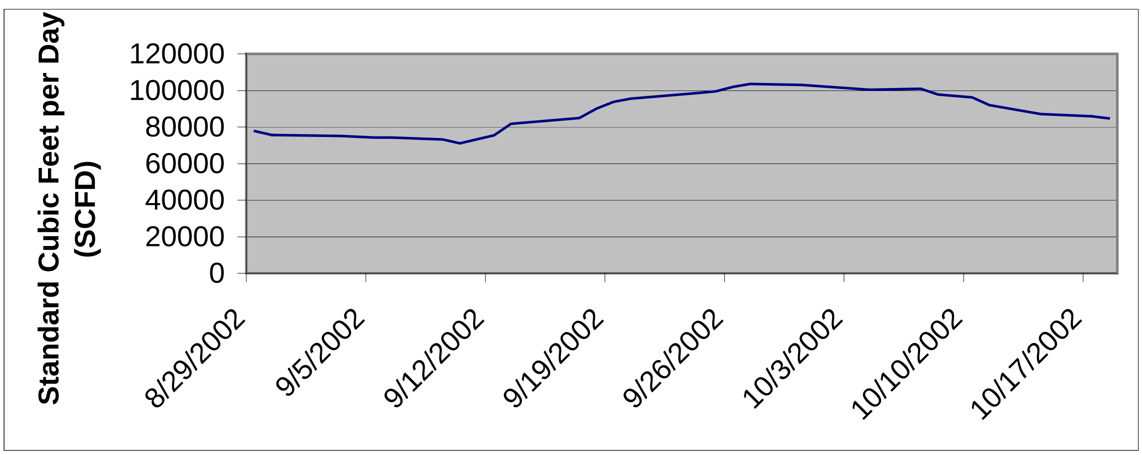
The raw manure flow rate can be seen in Figure 8.

FIGURE 8 –RAW MANURE FLOW RATE
(Aug 29 – Oct 20, 2002)



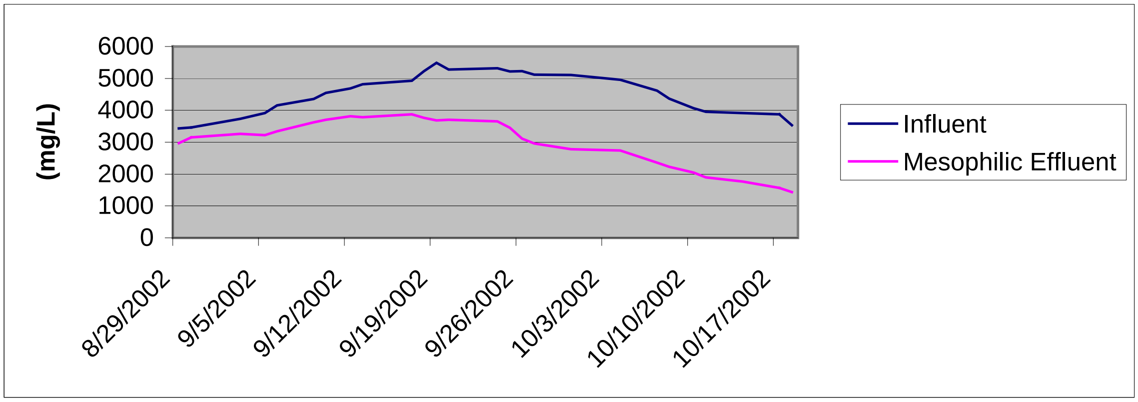
As noted previously, the data in the figures represent 15-day moving averages. Therefore, it should be noted that during the early part of the period raw manure was not being fed to the system. As outlined in Table 1, feed into the digester was completely shut off for several days and then very closely sanctioned for the remainder of the period, with the mesophilic effluent recycling rate varying throughout this operating period. Figure 9 shows the biogas generation during this operating period.

FIGURE 9 – BIOGAS GENERATION
(Aug 29 – Oct 20, 2002)



It can be seen in Figure 9 that the biogas generation did start to recover in the middle of September, which again corresponds to the reduction in the raw manure flow rate that occurred in late August. However, a reduction in the VFA levels in the digester did not occur as quickly, which can be seen in Figure 10.

FIGURE 10 – VOLATILE FATTY ACID CONCENTRATION
(Aug 29 – Oct 20, 2002)



In August and September, Figure 10 continued to shows an increasing trend in VFA concentration in both the system influent and effluent. The VFA concentrations in the effluent began to decrease in October, again corresponding to the lower ambient air temperatures during this time period and the associated reduction in anaerobic activity prior to the raw manure entering the anaerobic digestion system. The VFA concentration of the mesophilic effluent also started to decrease in October, demonstrating that the reduction in raw manure flow to the system had improved the performance of the anaerobic digestion system, but not yet to the point that the system was operating in May of 2002.

Figure 11 shows the volatile solids characteristics of the digester. It can be seen in Figure 11 that volatile solids in the mesophilic effluent changed very little over the course of this operating period. With the reduction in raw manure feed and the associated increase in detention time, it was expected that the volatile solids concentration found in the mesophilic effluent would decrease as the digester became healthier and more efficient. Figure 12 confirms that the anaerobic digestion system had not yet returned to the performance level that was observed during May of 2002. The percent volatile solids destruction reached a low in mid September at approximately 15%, more than 60% less than the 40% volatile solid destruction observed during the first operating period. However, it should be noted that the variable feeding rates of the raw manure and recycled mesophilic effluent, coupled with the limited number of samples that could be effectively collected, the data become more difficult to analyze during this operating period.

FIGURE 11 – VOLATILE SOLIDS
(Aug 29 – Oct 20, 2002)

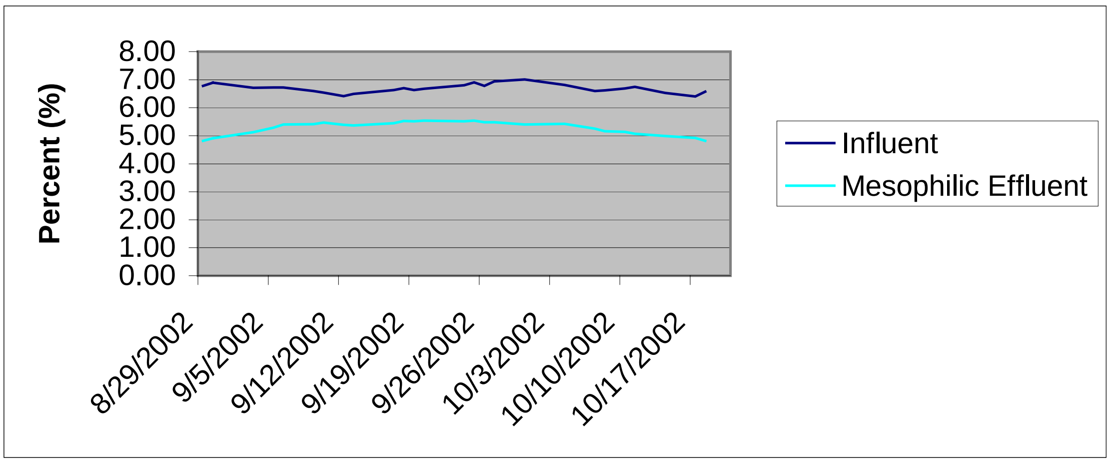
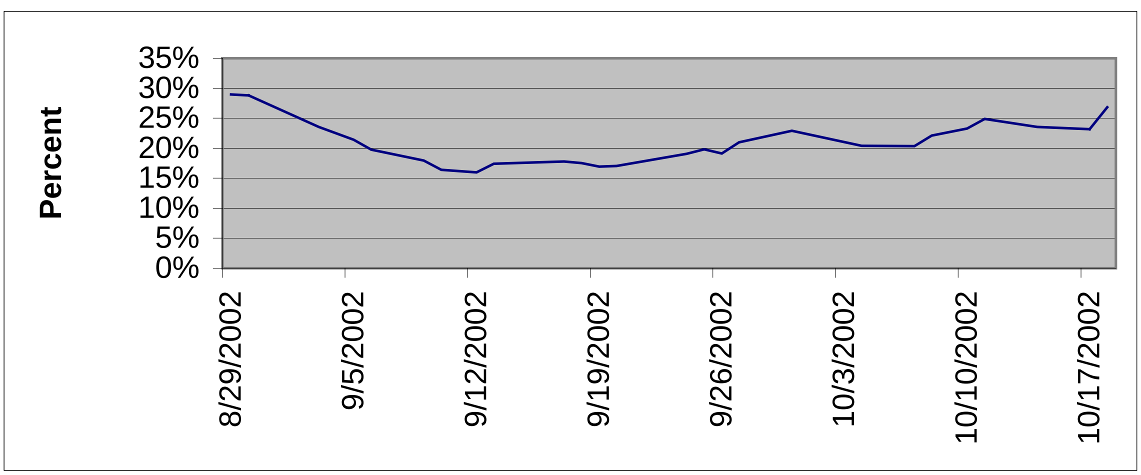


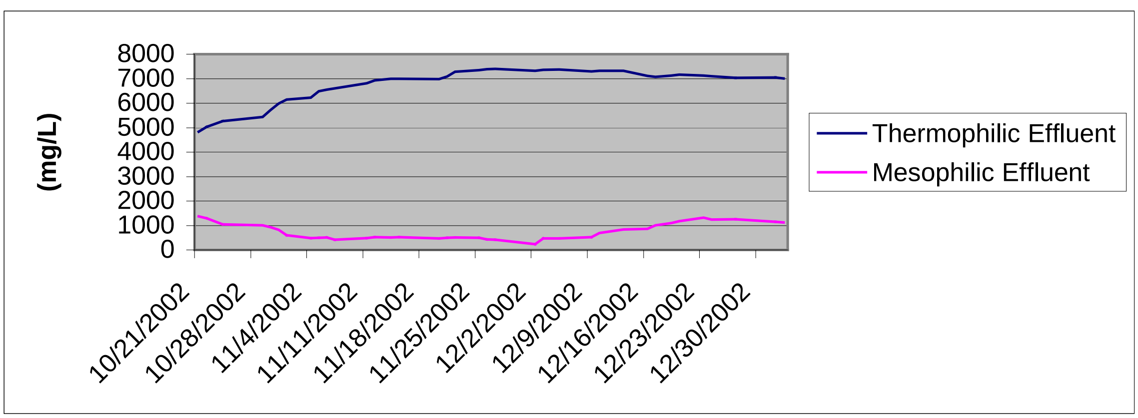
FIGURE 12 - VOLATILE SOLIDS DESTRUCTION BY PERCENT
(Aug 29 – Oct 20, 2002)



5.3 OPERATING PERIOD 3-THERMOPHILIC START-UP

As can be seen in Table 1, the third operating period occurred between October 21, 2002, and January 5, 2003. Due to the reduction in the VFA concentration of mesophilic effluent that occurred at the end of the previous operating period, it was decided in conjunction with Fox Engineering of Ames, Iowa, to begin transition of the digester to TPAD. The temperature in the thermophilic reactor was increased to 55°C while the temperature in the mesophilic reactor was maintained at 35°C. All external feed into the digester was stopped in an effort to continue to reduce the VFA concentration in both the mesophilic and thermophilic portions of the digester. Target concentrations for the thermophilic and mesophilic effluents were 3000 mg/L and 1000 mg/L, respectively, which was based on previous experience with starting TPAD systems at municipal wastewater treatment plants. However, it should be noted that the higher alkalinity of the dairy manure could minimize the potential for a significant drop in pH caused by increased VFA concentrations. Recycling was initiated with mesophilic effluent recycled back to the thermophilic reactor. This was done so that active bacteria would be recycled into the thermophilic reactor and to reduce the VFA concentrations in the thermophilic reactor by diluting with mesophilic effluent with a lower VFA concentration, reducing the potential toxicity caused by high VFA concentrations. Figure 13 shows the VFA concentrations in the thermophilic and mesophilic reactors of the digester during this operating period.

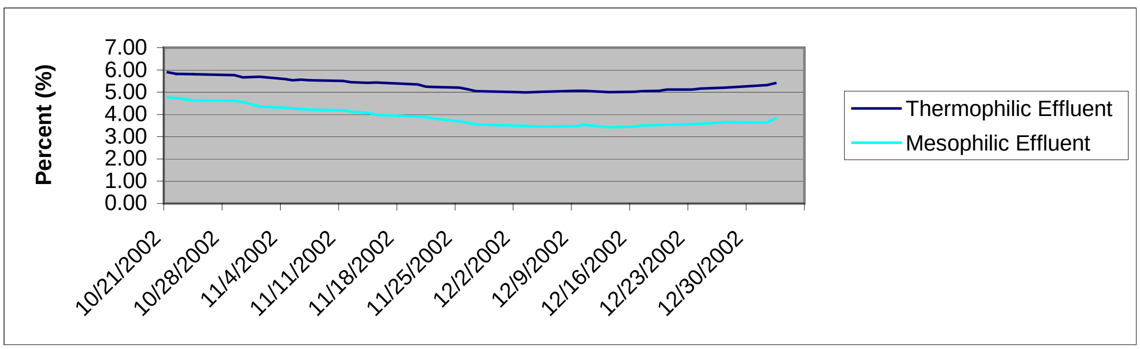
FIGURE 13 – VOLATILE FATTY ACID CONCENTRATION
(Oct 21– Jan 5, 2003)



Samples taken from the thermophilic reactor had VFA concentrations near 5000 mg/L at the beginning of this operating period. The increase in VFA concentration shown in Figure 13 indicates that efforts to reduce the VFA concentrations in the thermophilic portion through seeding and dilution failed. It was very evident that little or no reduction of VFAs occurred in this portion of the digester. Although biogas production from the thermophilic reactor could not be monitored separately, based on the increasing VFA concentrations it seemed to indicate that no biogas generation was occurring in the thermophilic reactor.

A reduction in VFA concentration in the mesophilic reactor did indicate that some biogas was being generated in the mesophilic reactor, which can be seen in Figure 14.

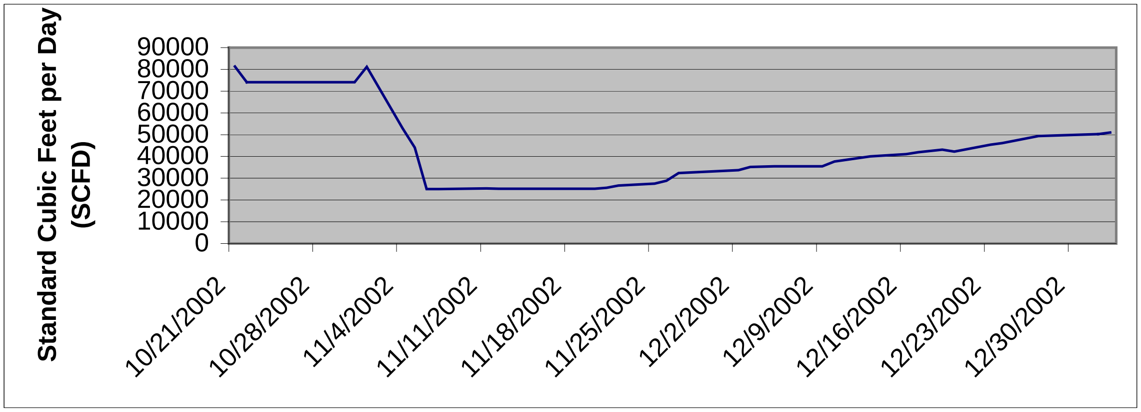
FIGURE 14 – VOLATILE SOLIDS
(Oct 21– Jan 5, 2003)



It can be seen in Figure 14 that the volatile solid for the thermophilic effluent and the mesophilic effluent decreased throughout much of the operating period. The decrease in volatile solids of the thermophilic effluent may be attributed to the dilution caused by the recycling of the mesophilic effluent back to the thermophilic reactor. Similarly, the decreasing volatile solids in the mesophilic effluent portion of the digester would also reflect this dilution, as seen by how closely the two lines in Figure 14 mirror each other.

Given the change to thermophilic temperatures, a significant reduction in the amount of biogas generation was observed several weeks later. This can be seen in Figure 15. Biogas generation did start to slowly increase during the later portions of this operating period, but was still significantly lower than levels achieved previously. As mentioned earlier, the methanogenic bacteria are the least stable of the anaerobic bacteria and are highly influenced by environmental change. Therefore, adjustments made to the anaerobic digestion system must be carefully considered.

FIGURE 15 – BIOGAS GENERATION
(Oct 21– Jan 5, 2003)

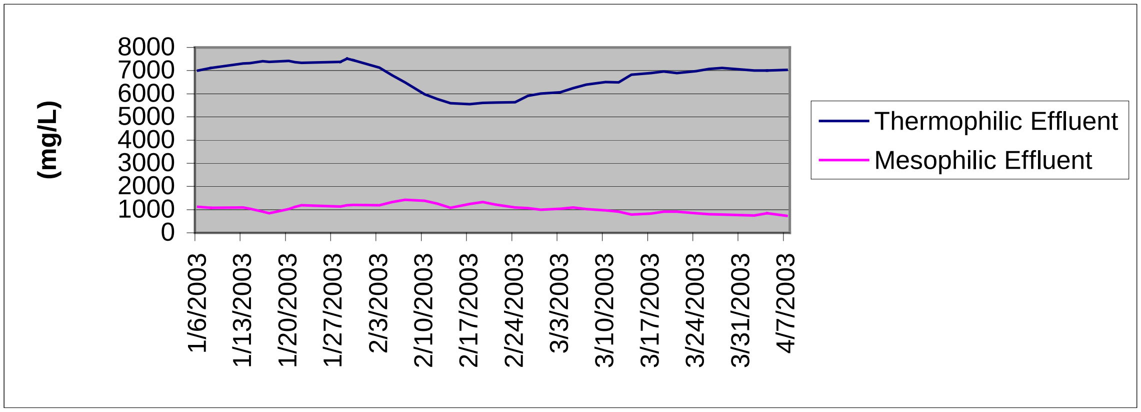


At the close of this operating period, biogas generation started to increase, but the VFA concentrations in the thermophilic reactor remained significantly higher that the desired levels. There is little evidence of biogas generation in the thermophilic reactor, but there is a reduction in the VFA concentrations in the mesophilic effluent.

5.4 OPERATING PERIOD 4-THERMOPHILIC OVERHAUL

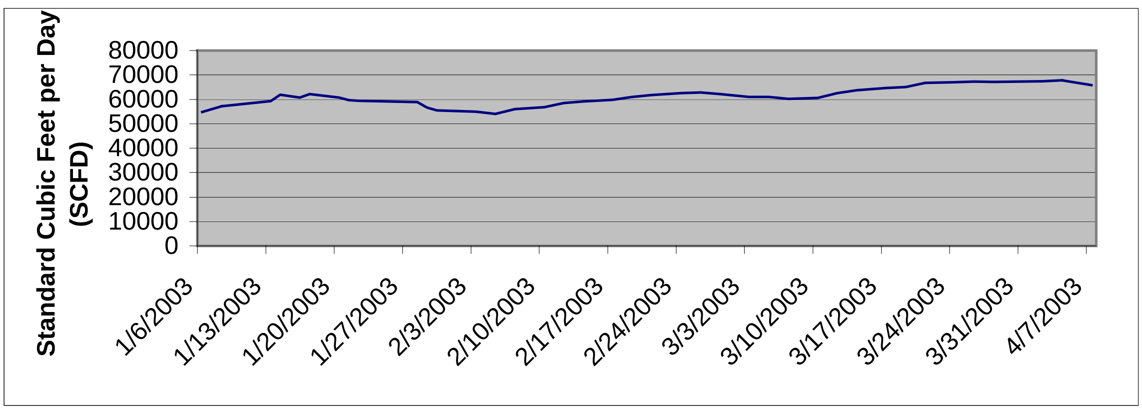
During this operating period, January 6, to April 8, 2003, the thermophilic and mesophilic reactors of the anaerobic digester were still operated independently. Feeding into the mesophilic reactor continued as normal in the previous period. Meanwhile, further action was taken to reduce the increasing VFA concentration found in the thermophilic reactor. Most notably, all feeding and recycling to the thermophilic reactor was stopped. Figure 16 shows the trend in VFA concentrations during this time period for both the thermophilic and mesophilic reactors. The VFA concentration goal was 3000 mg/L in the thermophilic reactor. However, during the course of this operating period, very little change in VFA concentration occurred, as the decrease in VFA concentration in February was followed by an increase in VFA concentration for the end of the operating period.

FIGURE 16 – VOLATILE FATTY ACID CONCENTRATION
(Jan 6 – April 8, 2003)



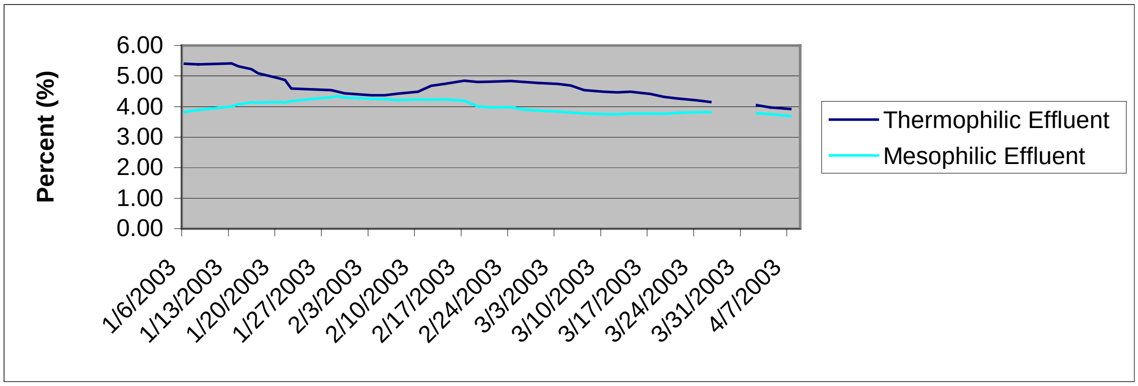
The stability of VFA concentration in the mesophilic reactor, which continued to be fed raw manure at increasing rates, should be noticed. Although the raw manure flow rate was increased, the VFA concentrations in the mesophilic effluent continued to decrease and the biogas generation continued to increase, which can be seen in Figure 17.

FIGURE 17 – BIOGAS GENERATION
(Jan 6 – April 8, 2003)



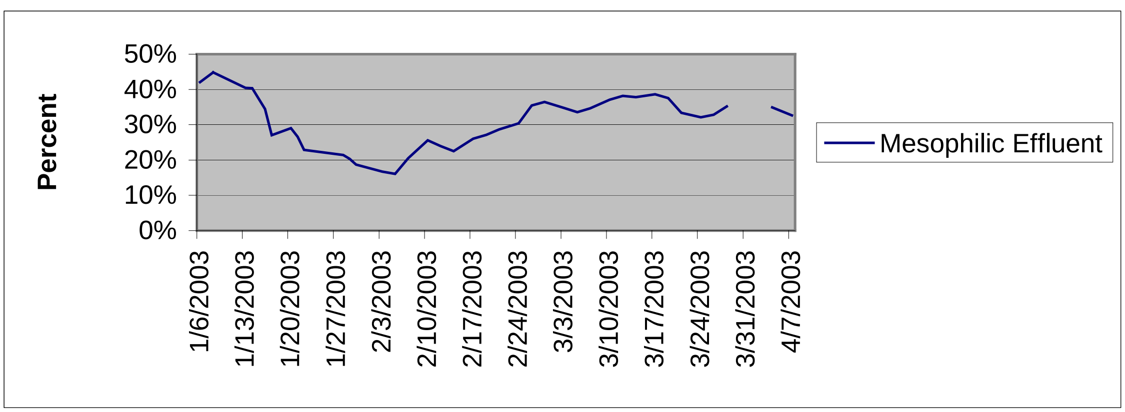
The biogas generation, which was thought to be occurring only in the mesophilic reactor, continued to increase, showing improved stability in the mesophilic reactor. This can also be seen in Figure 18, which shows the volatile solids concentration in the mesophilic effluent.

FIGURE 18 – VOLATILE SOLIDS
(Jan 6 – April 8, 2003)



It can be seen that the percent volatile solids in the thermophilic reactor decreased during this operating period. The mesophilic reactor, which was operated independent of the thermophilic reactor, again showed stability as the volatile solids stabilized at approximately 4% even though the raw manure loading rate was increased by 25% during the operating period. Figure 19 shows the volatile solids destruction for the mesophilic reactor.

FIGURE 19 - VOLATILE SOLIDS DESTRUCTION BY PERCENT
(Jan 6 – April 8, 2003)

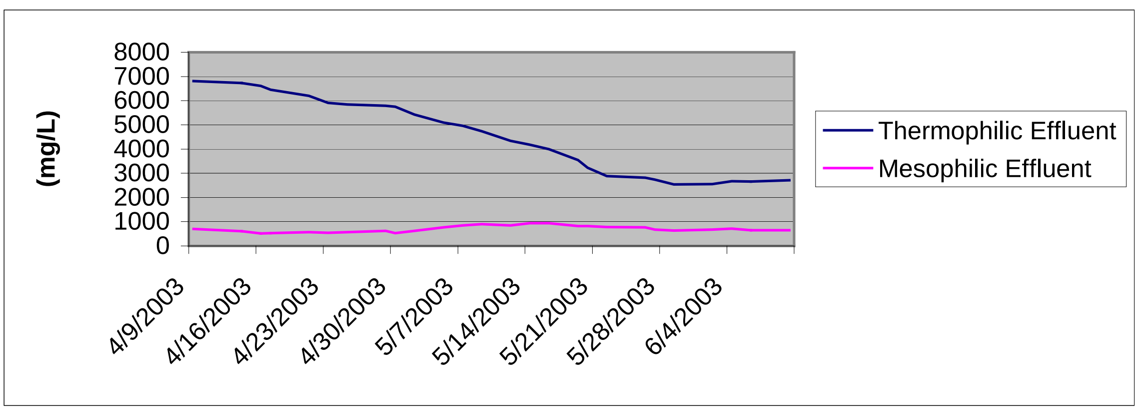


It can be seen in Figure 19 that the volatile solids destruction levels off at the end of the operating period near the level that it was during May of 2002. Again, this indicates that the health of the mesophilic reactor is nearing steady state and that portion of the anaerobic digestions system is operating effectively.

5.5 OPERATING PERIOD 5-TRANSITION TO TPAD

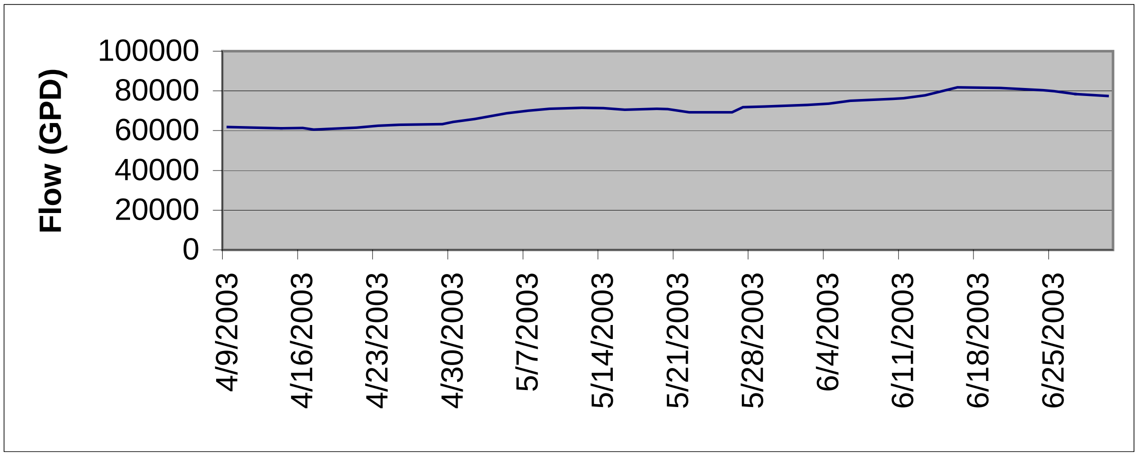
Although conditions in the mesophilic reactor continued to improve, actions taken to improve the thermophilic reactor continued to fail. Conditions in the thermophilic reactor had not changed during the previous period, with VFA concentrations remaining at approximately 7000 mg/L, more than twice the concentration desired. On April 9, 2003, it was determined that immediate action must be taken to reduce the VFA concentration in the thermophilic reactor in order to make the thermophilic process successful. Over the course of five days, 50% of the contents in the thermophilic reactor were wasted and this volume was then replace filled with low VFA mesophilic effluent in an effort to dilute the VFA concentration more manageable levels. Once the VFA concentration reached the desired 3000 mg/L in the thermophilic portion, the natural reduction of VFAs was expected to occur due to the less toxic environment. On May 20, 2003, it was determined that the VFA concentration in the thermophilic reactor was at appropriate levels and raw manure feeding was initiated to the thermophilic reactor. This marked the first time the digester was actually operated as a working TPAD system, with this method of operation continued throughout the remainder of the monitoring period for this project. Figure 20 shows the response in VFA concentration to the changes described above.

FIGURE 20 – VOLATILE FATTY ACID CONCENTRATION
(April 9 – Jun 30, 2003)



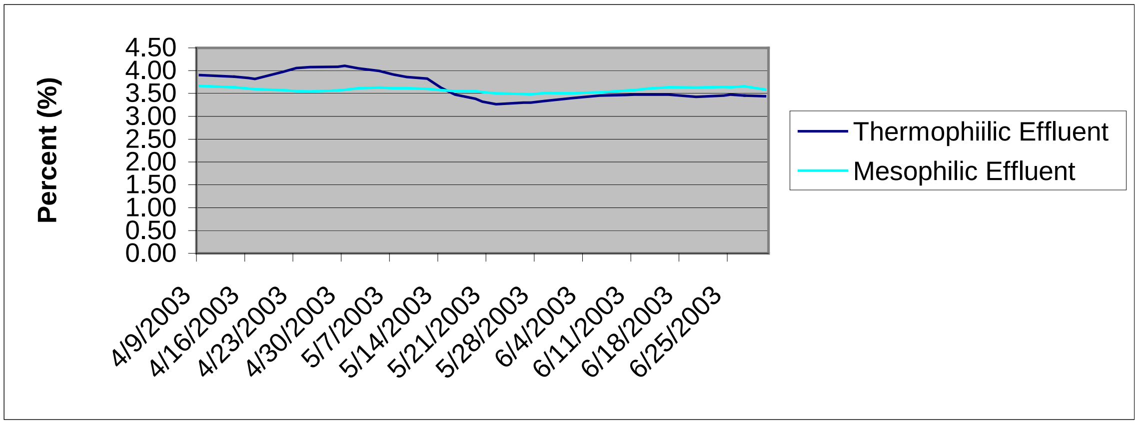
It should be noted that the reduction in VFA concentration from the 50% dilution does not show up immediately in Figure 20, again because the data in the graphs represent 15-day moving averages. The VFA concentration in the mesophilic reactor continued to remain stable throughout this final operating period, again proving the ability of this system to be successfully maintained as a mesophilic digester. As shown in Figure 21, the efforts to reduce the VFA concentration in the thermophilic reactor was successful, as the VFA concentration dropped to less than 3000 mg/L. With the VFA concentration below toxic levels, the thermophilic reactor should have responded with improved performance in the form of increased volatile solids destruction and biogas generation. Figure 21 shows the biogas generation within the digester.

FIGURE 21 – BIOGAS GENERATION
(April 9 – Jun 30, 2003)



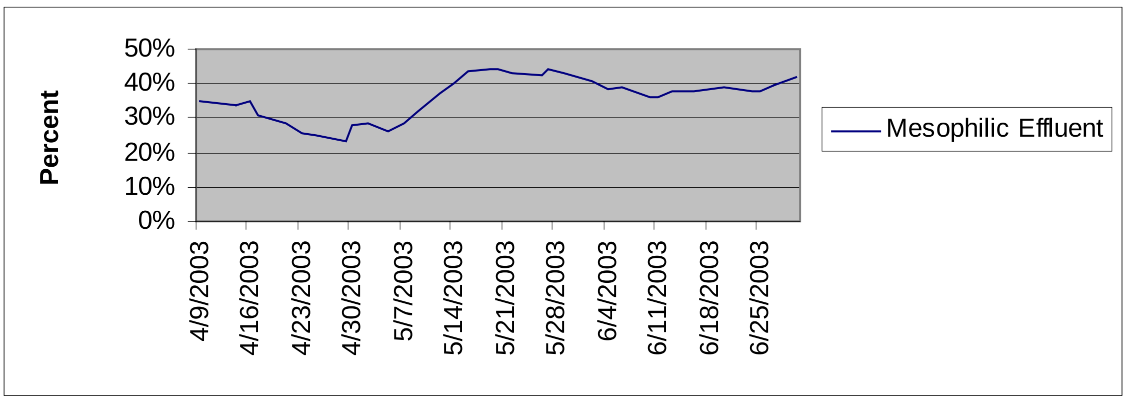
Biogas generation continued to increase during this time period. But it is questionable whether this was a response to the changes made in the thermophilic reactor or the increasing productivity in the mesophilic reactor. Figure 22 shows the percent volatile solids for the thermophilic and mesophilic effluent. Again, it can be seen that the mesophilic effluent remains consistent at approximately 4% volatile solids. It can also be seen that there is also a slight decrease in the volatile solids in the thermophilic effluent, but that decrease does continue even though the thermophilic reactor is being loaded with raw manure at a rate of only 5 gallons per minute during the majority of the operating period. However, a more substantial decrease in volatile solids concentration would be expected if the performance of the thermophilic reactor had improved substantially.

FIGURE 22 – VOLATILE SOLIDS
(April 9 – Jun 30, 2003)



The continued success of volatile solids destruction in the mesophilic reactor can be seen in Figure 23.

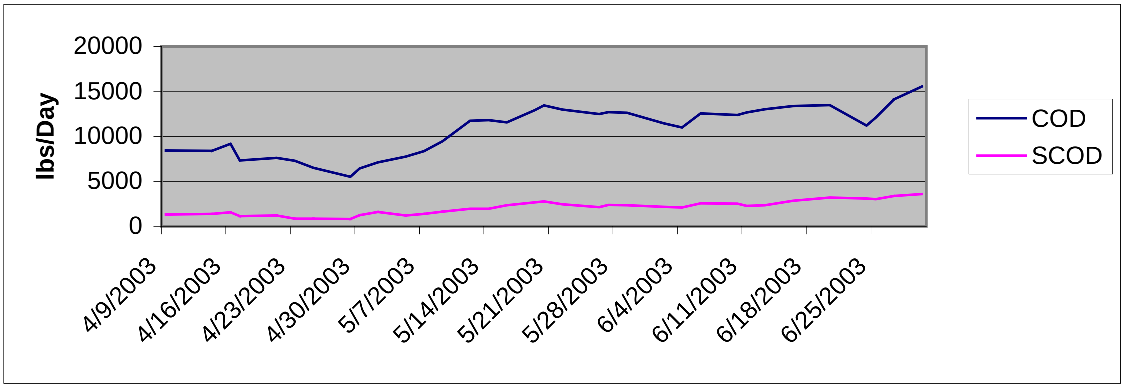
FIGURE 23 - VOLATILE SOLIDS DESTRUCTION BY PERCENT
(April 9 – Jun 30, 2003)



During the first part of this operating period, the volatile solids destruction in the mesophilic portion of the digester decreased slightly, but started to improve in late May. This may be attributed to the changes made in the thermophilic portion of the digester, as much of the thermophilic effluent that was wasted during early April was pumped into the mesophilic reactor.

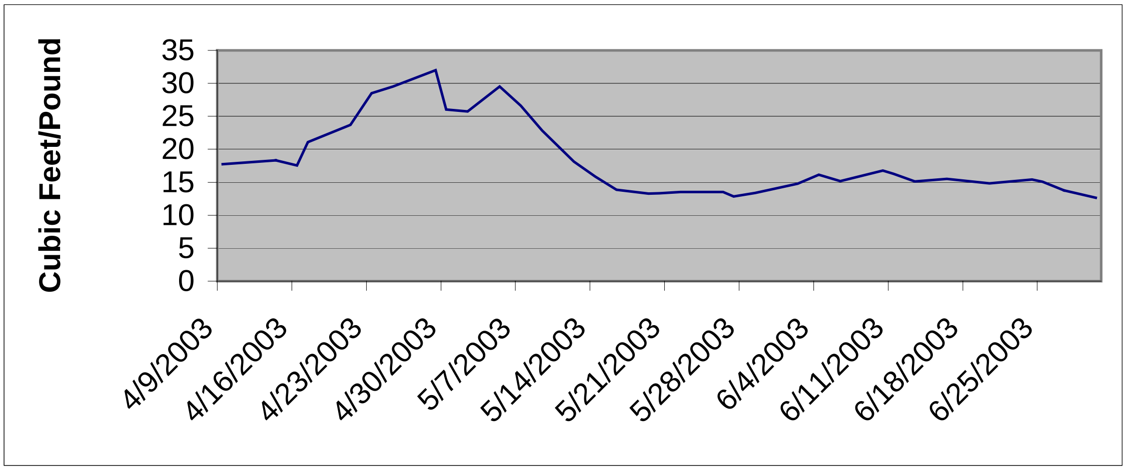
Figure 24 shows the COD and SCOD destruction in the mesophilic reactor.

FIGURE 24 – COD AND SCOD DESTRUCTION
(April 9 – Jun 30, 2003)



The trend observed in Figure 24 is very consistent with previous trends observed for volatile solids destruction. It should be noted that COD and SCOD destruction was again reaching levels maintained during the first operating period, again providing evidence that the mesophilic reactor continues to improve. The biogas generation versus volatile solids destruction, Figure 25, also stabilized at the end of this period in a similar range to the first operating period, approximately 15 cubic feet per pound of volatile solid destruction.

FIGURE 25 – BIOGAS VERSUS VOLATILE SOLIDS DESTRUCTION
(April 9 – Jun 30, 2003)



At the end of this operating period, there was still little indication that the thermophilic reactor was performing effectively. Therefore, it was determined by Tinedale Farms that the entire anaerobic digestion system would be converted back to the same operating protocol that was used during the first operating period, when the biogas generation was sufficient to run one engine-generator at capacity and also produce some additional biogas.

6.0 SUMMARY

Throughout the operation of the anaerobic digestion system at Tinedale Farms, several factors regarding the ongoing operations of the anaerobic digester system were determined. These include the following:

1) Operating as a complete-mix mesophilic system was found to be effective during the initial operating period, with biogas generation being adequate to run one 375-kW engine-generator and produce some additional biogas. It was anticipated that the biogas generation would have continued to increase beyond those levels seen during this period, but steady-state operation was not achieved and the maximum biogas generation at mesophilic temperatures was therefore not able to be determine.

2) Monitoring the raw manure flow rate and eliminating any excess water from rain events from entering the anaerobic digestion system was critical, as a significant decrease in digester performance was seen as the raw manure flow rate increased during June of 2002. Again, some of this may be attributed to a large rain event during the operating period, but additional flow also came from the use of misters in the barns to cool the animals. Therefore, the water use by the misters should be considered when the detention time of the anaerobic digestion system is determined.

3) Efforts to convert the anaerobic system to TPAD were largely ineffective, as shown under operating periods three through five. Several factors were thought to potentially contributed to the ineffectiveness of the thermophilic reactor, including the following: ongoing equipment issues that did not allowed steady-state operation of the anaerobic digestion system at entirely mesophilic temperatures or as a TPAD, (primarily related to ongoing operational issues with the two engine-generators), potential toxicity caused by high volatile fatty acid concentrations during startup of the thermophilic reactor (several efforts were made to address this factor), the potential toxicity of the raw manure other farm additives (antibiotics, chemicals for hoof treatments, etc.) on the thermophilic portion of the reactor.

4) Further information must be gathered regarding the potential factors limiting the effectiveness of TPAD in this application, as previous full-scale system at municipal wastewater treatment plants and laboratory studies on dairy manure have indicated that TPAD was effective.

Although the results of the TPAD operation at Tinedale Farm did not proceed as expected, the information described in this report should be helpful in providing information to others considering farm-based anaerobic digestion systems in general, and TPAD in particular.