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Preliminary Comparison of Five Anaerobic Digestion Systems on Dairy Farms in New York State

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Abstract. *As environmental regulations controlling direct land application of livestock waste increase, farmers search for ways to cost-effectively handle manure from their farms. Farmers' goals include efficient and effective means to remove the objectionable characteristics of their manure so that it may be recycled in an environmentally friendly manner. Anaerobic digestion is one way to control odors, liquefy manure and decrease pathogen loading, while reducing system costs by selling byproducts from the manure treatment process. Odor control allows digested effluent to be recycled in an environmentally and neighbor-friendly manner by applying it to cropland.*

Economic, nutrient, pathogen, energy production, and mass flows are under an ongoing quantification process for five integrated manure treatment systems in New York State. Each of these dairy farms has recently installed an anaerobic digester as a method to control odor. The currently available mass flow, nutrient flow, pathogen reduction, energy production and use, and economics of these systems are presented and compared. The systems vary by 1) type of digester: fixed film, plug flow, or mixed, 2) type of energy conversion: boiler, internal combustion engine, or micro turbine, 3) digester feed: scraped manure from freestalls, separated tie stall manure, or manure with food waste added, and 4) farm size.

Keywords. Anaerobic digestion, dairy manure, biogas production, economics, manure treatment, dairy facilities

Introduction

Farms are increasingly being required by their nutrient management plans (NMPs) to store manure, spread it close to the crop growing season, and utilize more fields to limit application to agronomic appropriate rates. These practices each increase the potential for odor conflicts with neighbors. While reducing their risk for water pollution, farms are facing increased opposition from those who object to the smell. Farms need a treatment method to obtain odor control that is effective, economical, and sustainable. Anaerobic digestion has been used and continues to be proposed as one method to treat manure to reduce odors and recover by-products. These systems have met with varying degrees of success on farms. Different types of anaerobic digesters have been researched and proposed as appropriate technology for on-farm use. Many farms are considering the application of anaerobic digestion to reduce odor that over time may provide a positive return to the farm. Each dairy farm is different and anaerobic digestion systems vary both in cost and in function.

This paper describes recently installed anaerobic digestion systems on five dairy farms in New York State, including the project background, basic system features, physical layout, and digestion characteristics of each system. Some important parameters (e.g. fecal coliform, COD, total solids, volatile solids and their reduction rates) are quantified for the initial period the systems have been operating and compared. Finally, the projected economics of these five anaerobic digester systems are compared and discussed.

Safety Emphasis

Methane digestion and biogas utilization do present some additional on-farm safety concerns. Biogas can be explosive in certain concentrations, it is flammable, and it does displace oxygen, which can lead to asphyxiation. Proper precautions such as flame arrestors and ventilation are important considerations. Posted warnings for employees regarding confined space entry are needed. Piping materials inside buildings should follow applicable codes. The electrical and mechanical equipment used to transfer influent and effluent and to utilize biogas need to be properly insulated to protect humans from harmful conditions. Interconnection to the public utility by the farmer as an independent power generator requires careful consideration and adherence to the utility's safety regulations.

Methods

Data for this project are being gathered generally on a monthly basis from each farm. Specialists collect representative influent and effluent samples, as well as samples of the separated liquids and separated solids. The samples are placed in a cooler with ice and delivered to a commercial lab for analysis of fecal coliform, Chemical Oxygen Demand (COD), Dissolved COD, Volatile Acids, TKN, $NH_{3,}$ pH, Potassium, Sulfate, and Total Hardness as $CaCO_3$, total phosphorus (TP), ortho – phosphorus, total solids (TS) and Total volatile solids (TVS). Samples taken from the digester influent and effluent were tested for *Mycobacterium avium* subspecies paratuberculosis (MAP). MAP is the microorganism responsible for Johne's disease in dairy cattle and other ruminants. This testing was not done on farms that did not have the disease.

The averages shown in table 1, 2, and 3 are from all data points collected with the exception of Farm FA. Farm FA digester operated as a fixed film digester from October of 2001 to June of 2003. Steady state operation results are reported from June of 2002 to April 2003. Tables 1,2,and 3 show the average values for this reported time period for Farm FA.

Hydraulic Retention Times (HRT) were based on the average influent divided by the operating volume.

The mass flow quantities were determined using a combination of timed volume outputs from pumps and calculations based on conservation of mass. Mass calculations assume that no settling occurs in the digester, that is, mass in equals mass out. We recorded flow amounts and pump run times for liquids. Mass flow out of the digesters on Farms AA and ML was determined by measuring the solid and liquid effluent from the separators and assuming that sum was the digester effluent. On Farms DDI, NH and FA, the mass flow out was calculated by subtracting the biogas mass from the influent mass.

Biogas amounts were calculated from VS destruction based on 15 ft^3 of biogas per pound of VS destroyed on all farms except Farm FA. Roots™ meter on Farm AA gave a reading within 2% of the calculated amount. On Farm FA the Roots™ meter gave a biogas production amount 33% more than the calculated value. The actual meter reading is reported in table 3 and used in calculations.

Economic analysis was done based on financial and operational data collected from producers and documents provided to the agencies involved showing actual costs where costs had been incurred. Projections on the life of equipment, salvage value, and repair costs were made consistently across each farm.

Farm Descriptions

Farm AA

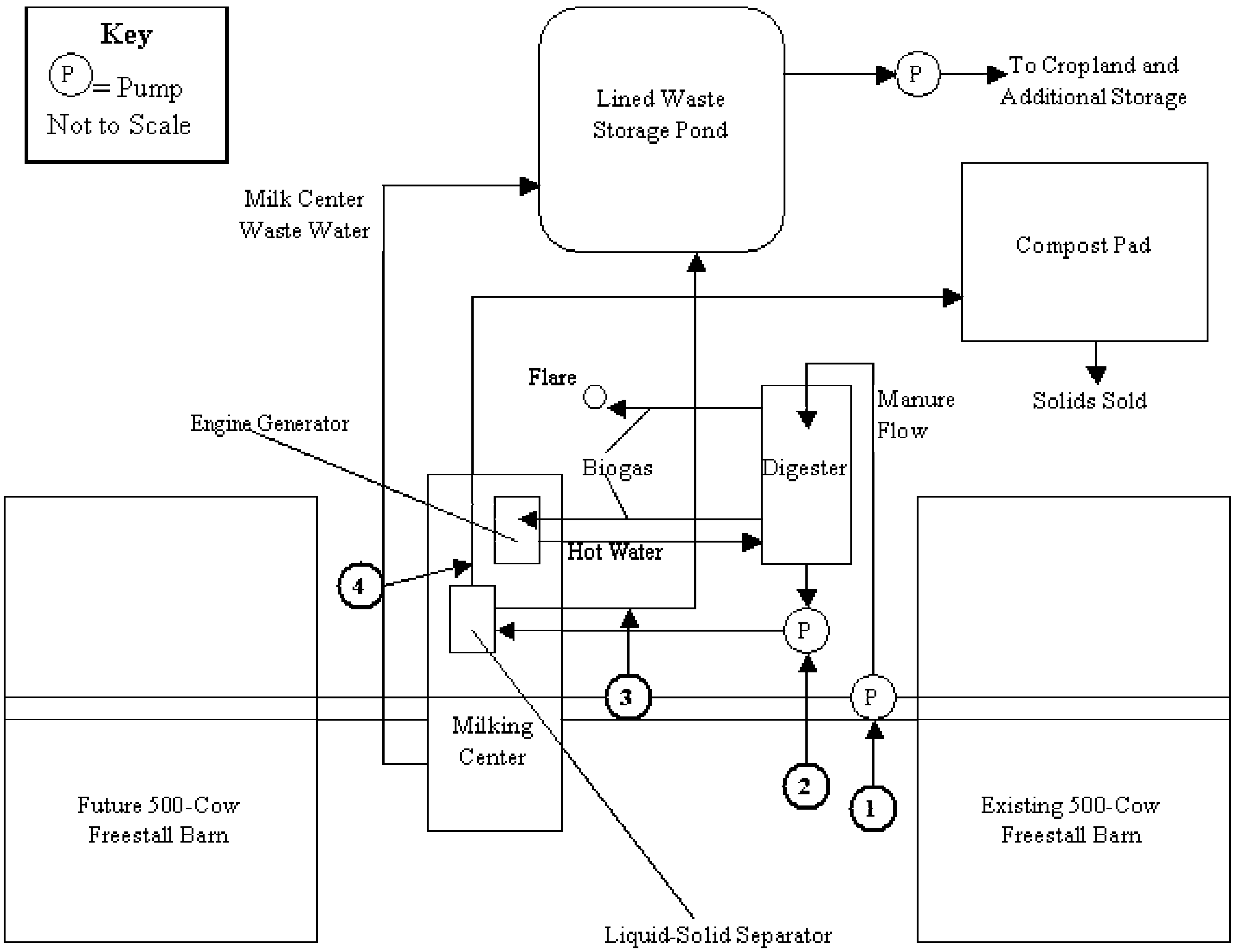
Farm AA is a 500-cow dairy operation with plans to expand to 1000 cows. The owner installed a plug-flow anaerobic digester in June 1998 with the primary objective of odor reduction. Feces, urine and bedding are fed into the digester. Digester effluent, mixed with milk house wastewater, flows by gravity to a storage pond. Tanker truck, and spray irrigation are used to apply effluent to cropland. The digester has operated continuously since the start-up. There has been some variation in the biogas output and occasional periods when the engine/generator was down for maintenance. A schematic of the system is in figure 1.

Before the anaerobic digester was built, manure and milking center wastewater were stored in an underground pit at the rear of the milking center holding area. Due to equipment problems and land application issues, the manure pit had to be emptied and land applied daily. Neighbors expressed concerns regarding odor, truck traffic, and a possible threat to water quality.

The 130 ft long, 30 ft wide and 14 ft deep anaerobic digester is constructed from concrete and is completely below grade. The digester is equipped with an airtight, expandable, flexible cover to contain biogas. The current resource recovery system consists of a solid-liquid manure separator, a 130 kW Caterpillar 3306 modified diesel engine connected to a generator, and a lined liquid-waste storage. Thermal and electric energy, digested fiber for compost, and liquid organic fertilizer are byproducts of the existing digestion system (Wright and Inglis, 2001).

Farm DDI

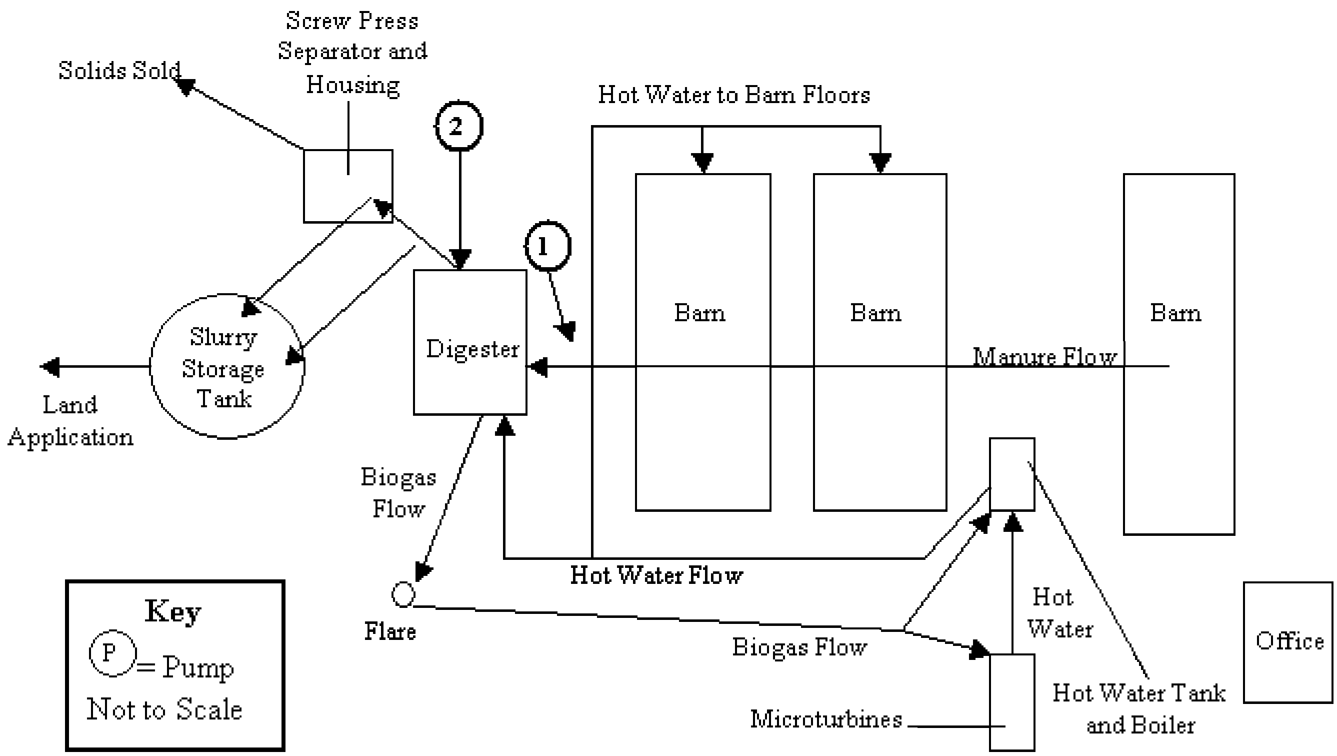
DDI is an 850-cow dairy constructed on a virgin site. The operation started in August 2001. A plug-flow anaerobic digester was part of the original design plans for manure management and odor control. Feces, urine and bedding are scraped to a gravity step-dam system located under the barns. Milking center wastewater is collected in a 21,000-gallon holding tank and is used to flush the holding pen. Some of the holding tank water is pumped regularly to the top of the flow gutter. This design allows for complete monitoring and control of water entering the flow gutter. One of the main reasons for this layout is to develop manure moisture content of 88% prior to digestion, which is considered ideal for plug-flow anaerobic digesters. The farm has experienced some trouble maintaining temperatures both in the start-up phase and during the recent cold winter. Extra wastewater that was not diverted has occasionally been added to the digester, causing a decrease in the HRT and some separation in the digester. A flow diagram for the system is shown in figure 2.



	Mass Flow (lbs/ day)	Moisture Content (%)
1 - Raw manure	91,700 (measured)	88.6
2 - Digester Effluent	80,700 (calculated)	91.7
3 - Separated Liquids	67,400 (measured)	95.0
4 - Separated Solids	13,300 (measured)	76.0
5 – Biogas	3,010 (calculated)	

Note: Accounting for mass in biogas there is 9% error in the above calculation.

Figure 1. Farm AA barns, manure handling, digestion, separation, and storage system.



	Mass Flow (lbs/ day)	Moisture Content (%)
1 - Raw manure	141,800 (measured)	91.0
2 - Digester Effluent	124,700 (calculated)	93.3
3 – Biogas	2,470 (calculated)	

Note: Accounting for mass in biogas there is 10% error in the above calculation.

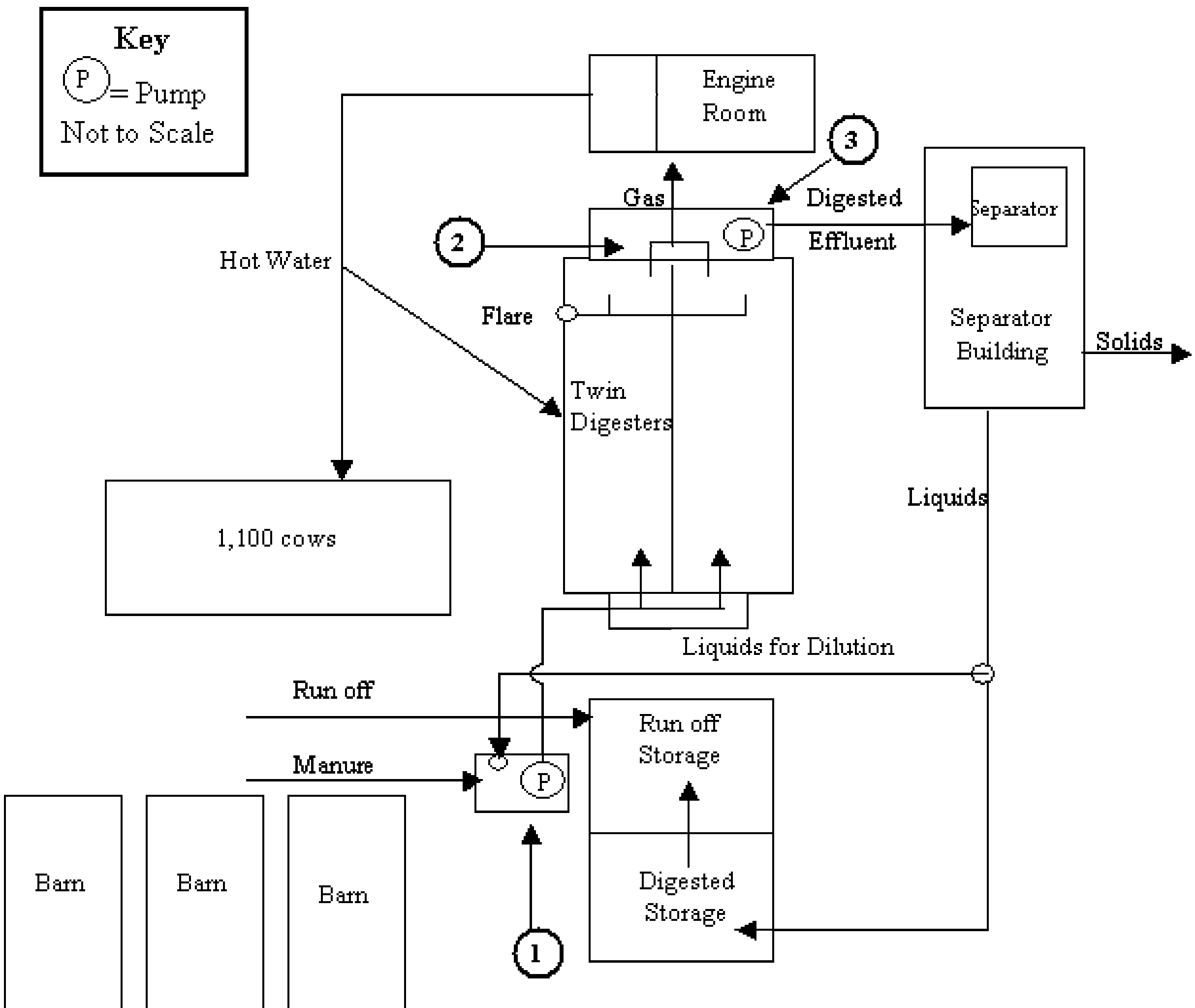
Figure 2. Farm DDI barns, manure handling, digestion, separation, and storage system.

Each barn is scraped using mechanical alley scrapers to the center, where the step-dam gravity flow system is located. An impeller-agitator is located in the reception pit that receives effluent from all barns. Approximately 17,000 gallons of manure and milking center wastewater are fed into the digester each day with a piston pump. The digester was constructed with concrete and is located below grade. It has an approximate retention time of 21 days, and is equipped with an airtight, expandable, flexible cover to trap biogas. Digested effluent is pumped directly to a slurry storage tank. The plan is to use biogas as an energy source for four 30-kW Capstone microturbines, which are in place but not operational at this time. Until the microturbines come online, a biogas boiler is used to heat the digester and supply hot water for the farm operation, as well as heat the floors throughout the barn. The digested effluent can be separated into solids and liquids. The screw press separator is located adjacent to the digester, and the farm is currently investigating potential markets for separated solids. Stored digested effluent is applied to cropland according to the farm's NMP (Wright and Inglis, 2003).

Farm NH

Farm NH is a 1,100-cow dairy. In January 2003 the farm installed an anaerobic digester and engine-generator system for odor control and to increase its business viability. The digester was sized for the current herd size with room for future expansion. The current retention time of the digester is about 25 days. Digester construction started in the summer of 2001, and the engine-generator set began operating on January 15, 2003.

The plug-flow digester is a rectangular below-grade concrete tank (120 ft x 50 ft x 16 ft). There are actually two digesters separated by a concrete wall as shown in figure 3. Manure (feces, urine and bedding) is scraped from each barn to a central gravity flow channel. Manure flows east to a collection pit (with a 28,000 capacity) located on the east side of the barns adjacent to an existing concrete storage. Manure is mixed with digested effluent and/or milking center wastewater to obtain 10% dry matter content and is then pumped to the digester influent manifold. The flow is distributed somewhat equally to the two parallel digesters twice a day.



	Mass Flow (lbs/ day)	Moisture Content (%)
1 - Raw manure	183,500 (measured)	91.0
2 - Digester Effluent 1	98,200 (calculated)*	92.0
3 – Digester Effluent 2	80,300 (calculated)*	92.5
4 – Biogas	5,000 (calculated)	

*Note: The flow into the two digesters varies with moisture content of the pumped influent. An average 10% difference was assumed.

Figure 3. Farm NH barns, manure handling, twin digestion, separation, and storage system sized for 1,100+ cows.

The NH digester has a flat cover made of pre-cast concrete panels covered with poured-in-place concrete, insulation and earth. The digester is sealed from inside to prevent biogas leakage and insulated to maintain temperature. The digester is maintained at 0.54 psi. A sediment trap with a suction pump access was built inside the digester to allow removal of accumulated grit as needed. Once the separator building is completed and other necessary equipment is installed, manure will be pumped from the effluent chamber to an elevated separator. The separated solids will be composted and used as soil amendment in the cropping program or sold. The separated liquids will flow to the concrete storage by gravity. Some of the liquids may be recycled and used to adjust the manure solids content prior to entering the digester. This digester was slowly brought up to temperature during the winter of 2003. The digester also had reduced feed during the winter of 2004 due to frozen manure being excluded from the system. The temperature of the digester was not maintained at the optimum from January to April 2004. The schematic of this operation is shown in figure 3. The engine (Caterpillar 3406 NA, 285 HP) is attached to an electrical generator (Marathon 447) with a capacity of 130 kW (Wright, P. E., and J. Ma. 2003c).

Farm ML

The mixed digester at Farm ML was designed for 675 milking cows and for food waste, or 1,500 cow equivalents. It was built in December of 2001 to address a variety of objectives, including odor control, nutrient management, and increased revenue. The digester is a complete mix unit with a rectangular concrete tank located below grade. Its dimensions are 78 ft long x 68 ft wide x 16 ft deep. The digester was built in the hillside to utilize gravity flow throughout the system. Manure, (urine, feces, and bedding) and trucked-in food waste is gravity fed to the digester. A flexible, impermeable cover on the digester contains the generated biogas. The amount of food waste added to this digester has a large impact on its functioning. The amount and type of food waste varies by season and with the operation of the food processing plants that generate it. The schematic in figure 4 shows the manure management system for this farm.

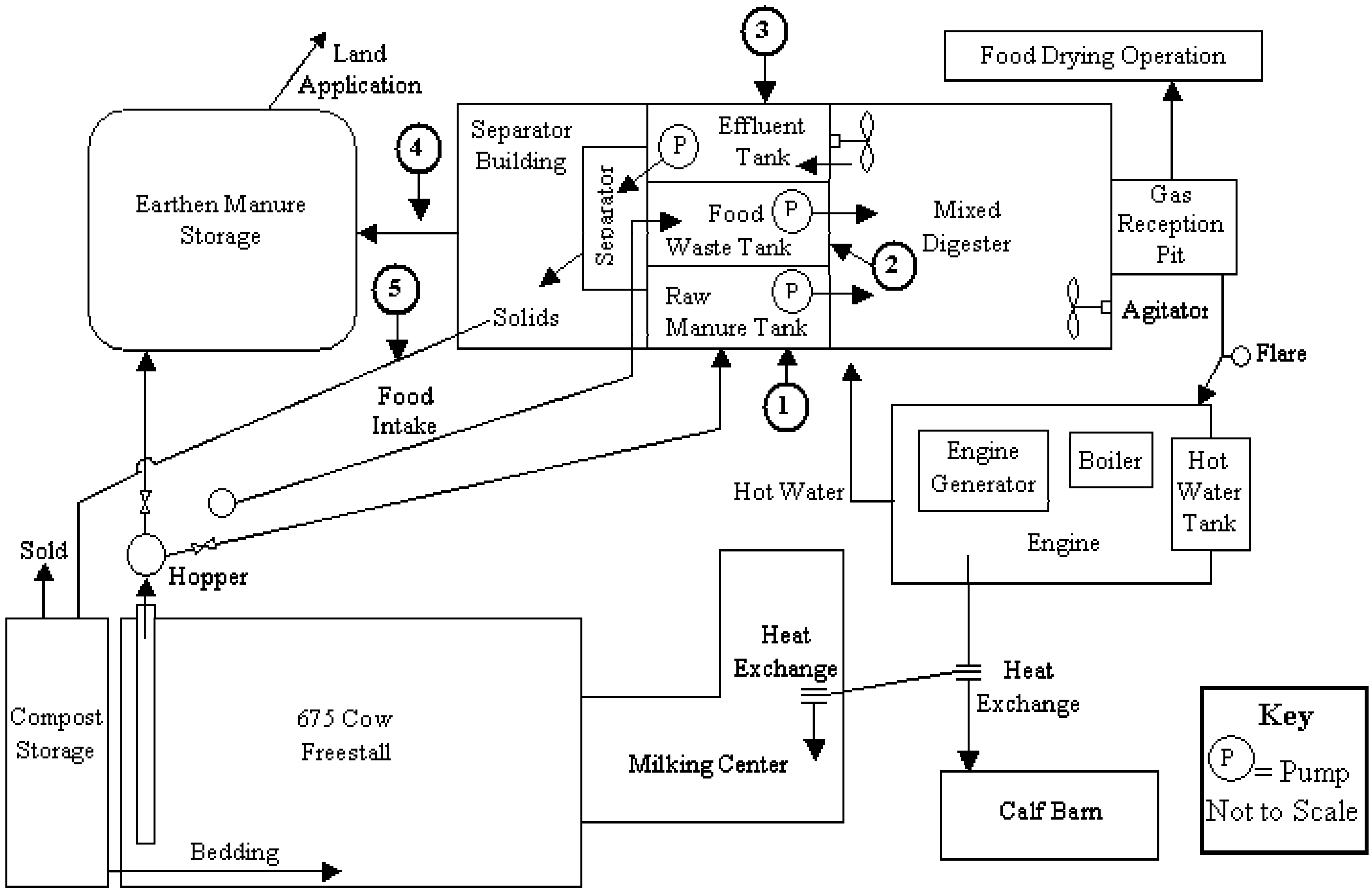
Manure is scraped daily and gravity flows to a collection pit. Two 20-hp manure pumps fixed at two opposite corners of the digester operate two hours per day to mix the manure/food waste mixture. The digester's retention time is about 20 days. The food waste streams are introduced to the digester as they come to the farm and a substantial tipping fee is collected from the food generators. The resulting mixture substantially increases the biogas production and also increases the methane content of the biogas (Wright and Inglis, 2003).

Farm FA

This 100-cow tie stall dairy used a liquid manure storage system for 10 years prior to building an anaerobic digester. Complaints about odor from neighbors and area visitors are the main reason the farm installed a fixed-film digester. The farm is located in the New York City watershed. Farms in the watershed are encouraged to control pathogens and reduce phosphorus loading on cropland. The watershed's policy is to cover the capital costs incurred for manure management projects on qualified farms. As with the other projects, the economic data is presented as if the farm had to cover the complete system costs itself.

The fixed-film digester requires solid-liquid manure separation prior to digestion. The digester is an externally insulated, 10.5 ft diameter by 16 ft high pre-cast, sectional concrete tank. The fixed-film media was corrugated plastic drainage tile (CPDT) bundled together and set upright inside the digester, providing microbes a total of 12,000 square feet of surface area for attachment. The system had a 4-day retention time. The digester produced 2,400 ft^3/day (24 ft^3/cow-day) of biogas. This was enough biogas to heat the digester through two winters in the

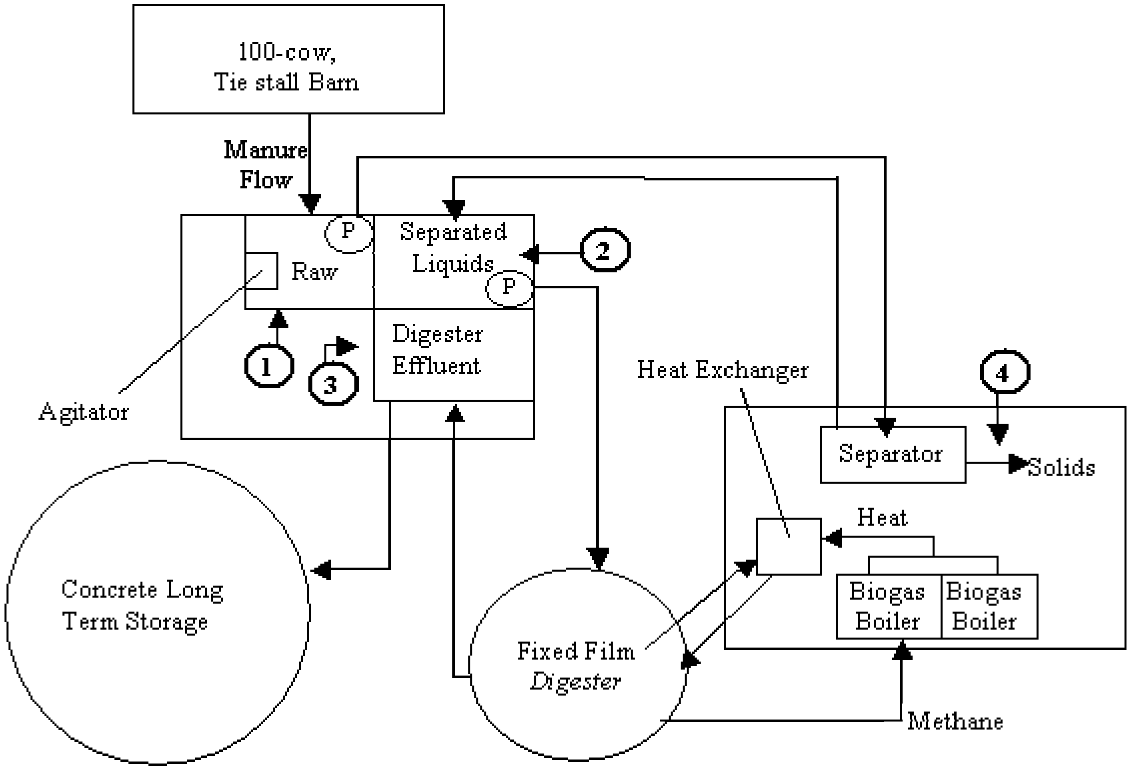
Catskill region of New York State. This digester operated as a fixed-film system from October of 2001 to June of 2003. Steady state operation results are reported from June 2002 to April 2003. A calcium buildup on the CPDT began to impact the digester in May 2003. The added calcium was from a calcite product added to the floors and stalls of the barn. After discovering the buildup, the fixed film was removed and the digester operated as a high-rate vertical plug-flow digester. A schematic layout of the system is shown in figure 5.



	Mass Flow (lbs/ days)	Moisture Content (%)
1 - Raw manure	111,800 (measured)	87.5
2 - Food Waste	93,400 (measured)	82.4
3 - Digester Effluent	172,400 (calculated)	94.5
4 - Separated Liquids	170,300 (measured)	94.4
5 - Separated Solids	2,100 (measured)	69.0
6 – Biogas	19,500 (calculated)	

Note: Accounting for mass in biogas there is 6% error in the above calculation.

Figure 4. Farm ML barns, manure handling, mixed digester, separation, and storage system sized for 675 cows. The mixed digester accepts food waste as well as manure.



	Mass Flow (lbs/ day)	Moisture Content (%)
1 - Raw manure	16,900 (measured)	90.4
2 - Separated Liquids	13,500 (measured)	95.1
3 - Digester Effluent	13,300 (calculated)	96.2
4 - Separated Solids	3,400 (measured)	73.2
5 – Biogas	170 (measured)	

Figure 5. Farm FA barns, manure handling, separation, solid handling, fixed film digester, and storage system sized for 100-cow tie stall barn.

Approximately 1,900 gallons of manure (feces, urine, and bedding and calcite) is deposited daily in the manure gutters located below each row of tie stalls. A gutter cleaner delivers manure into a 2-day reception pit where milk house wastewater is also added. Clean water can also be added as needed to create pumpable slurry to the screw-press separator, which processes 2,000 gallons per day. The separator produced on average 1,620 gallons of liquids and 140 cubic feet of solids per day (Weeks, 2003).

Results

The five farms described above have been part of a research project over the last three years. After digester construction was complete, manure samples were taken monthly at key locations for each system as shown in figures 1-5. The data reported for Farms DDI, NH, and ML include times when the digesters, due to start-up conditions or other operating upsets, may not have been operating as designed. Farm AA data do include some variations in operating conditions but not the start-up data. Farm FA was operating as designed as a fixed-film digester from October of 2002 to June of 2003. The data shown only represent from June 2002 to April 2003.

These points describe the influent and effluent of the digester, and the separated liquids and solids when a separator is running consistently on each farm. There were times when the separators for Farms AA and ML were not working. Farm DDI rarely used its separator and Farm NH does not have its separator installed yet. The manure samples were analyzed for a wide range of characteristics. A summary of the analyses is shown in tables 1 and 2. Care should be taken when using this data and comparing these analyses since the operating conditions on each farm are different.

Table 1. Sample results from five digester systems including: pathogens and parameters related to biogas production. SD is the standard deviation for the sample set and n is the number of samples.

	Johnes (CFU/gram)	Fecal Coliform (MPN/gram)	Volatile Acids (mg/kg)	Chemical Oxygen Demand (mg/kg)	Dissolved COD (mg/kg)	Total Solids (%)	Total Volatile Solids (%)
Farm AA Raw Manure							
Average	12,083	3,625,406	3,371	134,695	24,766	11.42	84.15
SD	8,789	5,112,928	960	189,311	7,447	1.00	1.27
n	55	64	13	63	63	63	63
Farm AA Digester Effluent							
Average	134	3,646	496	94,148	15,848	8.30	78.65
SD	233	4,711	174	82,799	5,318	1.02	5.96
n	54	60	13	63	63	63	63
Farm AA Separated Liquids							
Average	77	2,789		54,872		5.04	70.45
SD	241	5,608		16,605		0.88	1,594
n	48	58		58		58	58
Farm AA Separated Solids							
Average	20	803		153,695		24.03	88.71
SD	80	2,298		100,265		2.18	2.09
n	53	55		57		57	57
Farm DDI Raw Manure							
Average	7,650	1,925,000	3,410	121,987	21,281	9.01	82.88
SD	7,744	2,504,433	793	84,025	6,035	1.27	1.74
n	6	16	12	15	15	16	16
Farm DDI Digester Effluent							
Average	66	11,301	1,512	110,658	16,406	6.75	78.77
SD	46	8,691	1,058	168,442	3,989	1.24	4.07
n	5	15	12	15	15	16	16
Farm FA Raw Manure (for the period 6/5/02 to 4/25/03)							
Average		675,833		109,723	23,078	9.58	80.72
SD		859,603		33,227	5,323	1.20	2.28
n		12		8	8	12	12
Farm FA Separated Liquids (for the period 6/5/02 to 4/25/03)							
Average		620,191	2,798	53,318	22,246	4.87	67.73

SD		639,527	830	3,724	4,187	0.38	4.91
	Johnes (CFU/gram)	**Fecal Coliform (MPN/gram)**	**Volatile Acids (mg/kg)**	**Chemical Oxygen Demand (mg/kg)**	**Dissolved COD (mg/kg)**	**Total Solids (%)**	**Total Volatile Solids (%)**
n		12	12	8	8	12	12
Farm FA Digester Effluent (for the period 6/5/02 to 4/25/03)							
Average		8,930	929	42,416	15,900	3.80	64.31
SD		10,443	483	14,388	4,138	0.37	3.39
n		11	12	8	8	12	12
Farm FA Separated Solids (for the period 6/5/02 to 4/25/03)							
Average		223,416		189,022	17,353	26.85	89.73
SD		192,240		75,741	5995	2.51	1.46
n		12		8	8	12	12
Farm ML Raw Manure							
Average	8,278	606,833	3,323	137,547	39,178	12.46	88.27
SD	6,011	620,742	1,525	31,309	7,760	4.13	3.99
n	4	12	12	11	10	12	12
Farm ML Food Waste							
Average	0	434	5,081	271,945	41,643	17.60	91.36
SD	0	661	2,095	232,792	17,214	18.60	6.18
n	2	11	11	10	10	11	11
Farm ML Digester Effluent							
Average	285	18,308	386	63,996	12,866	5.55	77.51
SD	336	26,416	130	8,325	3,371	0.55	1.40
n	4	12	12	11	10	12	12
Farm ML Separated Liquids							
Average	231	5,203		77,202	21,170	5.58	79.27
SD	377	6,712		15,642	10,118	0.89	3.28
n	4	12		11	5	12	12
Farm ML Separated Solids							
Average	6	8,911		249,212	17,651	31.04	92.65
SD	7	15,458		76,257	8,212	5.09	1.40
n	4	11		11	5	12	12
Farm NH Raw Manure							
Average	2,888	872,222	2,885	72,100	23,363	8.99	80.22
SD	3,341	999,009	1,170	33,814	11,442	3.00	1.91
n	2	9	9	9	9	9	9
Farm NH Digester 1 Effluent							
Average	64	9,488	520	65,627	19,515	7.99	74.31
SD	58	16,559	255	22,532	4,945	1.31	2.56
n	2	8	9	9	9	9	9

	Johnes (CFU/gram)	Fecal Coliform (MPN/gram)	Volatile Acids (mg/kg)	Chemical Oxygen Demand (mg/kg)	Dissolved COD (mg/kg)	Total Solids (%)	Total Volatile Solids (%)
Farm NH Digester 2 Effluent							
Average	27	13,913	591	61,823	17,326	7.52	74.30
SD	22	8,778	496	23,541	6,390	1.98	23.05
n	2	8	9	9	9	9	9

Table 2. Sample results from five digester systems including nutrient characteristics. SD is the standard deviation for the sample set and n is the number of samples.

	Ammonia (mg/kg)	Total Kjeldahl Nitrogen (mg/kg)	Total Phosphorus (mg/kg)	Ortho Phosphorus (mg/kg)	Potassium (mg/kg)	pH (Std units)	Sulfate (mg/kg)	Total Hardness (mg/kg $CaCO_3$)
Farm AA Raw Manure								
Average	1,916	4,960	839	472	119	7.21	350	4,872
SD	471	1,256	227	128	167	0.30	187	2,291
n	63	63	63	63	5	63	7	4
Farm AA Digester Effluent								
Average	2,618	5,286	857	551	115	7.92	<100	5,389
SD	431	1,215	204	113	168	0.09		3,125
n	63	63	63	63	5	63	4	6
Farm AA Separated Liquids								
Average	2,491	4,731	768	519	101	7.90		
SD	663	1,594	191	150	128	0.18		
n	58	58	58	58	4	58		
Farm AA Separated Solids								
Average	2,518	6,053	1,208	643	127	8.52	<100	
SD	426	1,748	323	174	182	0.15		
n	57	57	57	57	4	57	2	
Farm DDI Raw Manure								
Average	1,726	3,432	513	256	104	7.45	202	5,604
SD	382	453	102	71	150	0.46	98	2,149
n	126	16	16	16	6	16	7	6
Farm DDI Digester Effluent								
Average	2,207	3,462	512	291	80	7.63	<100	3,768
SD	429	336	130	81	102	0.16		1,181
n	16	16	16	16	6	16	9	6
Farm FA Raw Manure (for the period 6/5/02 to 4/25/03)								
Average	2,218	3,893	635	384		7.45		
SD	323	359	73	48		0.15		
n	12	12	12	12		12		

	Ammonia (mg/kg)	Total Kjeldahl Nitrogen (mg/kg)	Total Phosphorus (mg/kg)	Ortho Phosphorus (mg/kg)	Potassium (mg/kg)	pH (Std units)	Sulfate (mg/kg)	Total Hardness (mg/kg $CaCO_3$)
Farm FA Separated Liquids (for the period 6/5/02 to 4/25/03)								
Average	2,214	3,846	634	360		7.43	312	
SD	321	663	89	47		0.11		
n	12	12	12	12		12	1	
Farm FA Digester Effluent (for the period 6/5/02 to 4/25/03)								
Average	2,466	3,712	592	414		7.75	120	
SD	281	523	61	29		0.08		
n	12	12	12	12		12	1	
Farm FA Separated Solids (for the period 6/5/02 to 4/25/03)								
Average	1,558	3,340	525	306		8.24		
SD	417	658	95	80		0.22		
n	12	12	12	12		12		
Farm ML Raw Manure								
Average	1,349	3,375	671	402	78	5.64	246	
SD	623	1,024	225	157	48	0.94	117	
n	12	12	12	12	4	12	5	
Farm ML Food Waste								
Average	718	2,593	519	256	45	4.15	100	5,940
SD	233	709	228	119	14	0.71	0	2,596
n	11	11	11	11	3	11	1	4
Farm ML Digester Effluent								
Average	1,472	3,274	584	350	51	7.61	303	5,061
SD	175	368	148	78	17	0.14	287	2,212
n	12	12	12	12	4	12	2	3
Farm ML Separated Liquids								
Average	1,353	3,114	586	342	68	6.98	100	3,861
SD	222	362	106	109	37	0.80	0	887
n	12	12	12	12	4	12	1	4
Farm ML Separated Solids								
Average	1,310	5,232	1,026	566	77	6.21	100	6,915
SD	337	1,650	267	160	41	1.23	0	0
n	12	12	12	12	4	12	1	1
Farm NH Raw Manure								
Average	1,687	4,008	439	180	136	7.45	229	6,387
SD	784	1,120	189	73	221	0.41	111	3,317
n	9	9	9	9	5	9	7	5

	Ammonia (mg/kg)	Total Kjeldahl Nitrogen (mg/kg)	Total Phosphorus (mg/kg)	Ortho Phosphorus (mg/kg)	Potassium (mg/kg)	pH (Std units)	Sulfate (mg/kg)	Total Hardness (mg/kg $CaCO_3$)
Farm NH Digester 1 Effluent								
Average	2,301	4,152	468	289	79	7.74	112	5,194
SD	480	628	63	18	101	0.09	17	2,114
n	9	9	9	9	5	9	2	5
Farm NH Digester 2 Effluent								
Average	2,194	3,786	487	262	121	7.67	335	4,645
SD	867	1,346	171	95	153	1.78	175	2,493
n	9	9	9	9	5	9	2	5

Discussion

Based on the data in table 1, the values of total volatile solids, total solids, and volatile acids are consistent for raw manure collected from the five farms. Most modern dairies in New York are consistent in the basic diet they feed the animals. About half the diet consists of homegrown forage and the other half is purchased feeds. Forage quality can vary, and the make-up of the grains changes depending on the milk production and price of the different types of grain. Foaming responses from the digesters have been noted with some dietary changes.

The levels of fecal coliform and COD were observed to be extremely variable on all five farms (table 1). Fecal coliform, used as an indicator organism for potential pathogens, can vary greatly from sample to sample on the same farm. Besides sampling and testing errors, the organisms are not that hardy and may be influenced by environmental impacts as it is collected or even as it is shed. COD variation is hard to explain except as sampling and/or testing errors.

Among the five farms, Farm ML is the only one, which adds food waste to its digester. Many of the comparison parameters in table 3 reflect this difference. The fecal coliform in the food waste was lower as expected, precisely because it is food waste and not fecal matter like the manure. The volatile acids in the food waste were much higher, indicating that the digestibility would be high as well. The pH of the food wastes was lower, which could be a problem if the food waste was digested alone, since methanogenic bacteria are susceptible to low pH; however, the manure in the digester buffers the pH of the food waste.

The nutrient levels in the food waste imported by Farm ML were not very different compared to the nutrients in the raw manure on all five farms (table 2). Food wastes can vary from load to load, but in general they have a larger available energy to the digester with about the same proportion of nutrients compared to raw manure. Overall, Farm ML has the highest solids reduction rates compared to all the other farms (see table 3), which probably means the digester is much more efficient at reducing odor and producing biogas, due to the mixture of food waste with the manure.

Farm ML produces 250,400 $ft^{3/}$day of biogas as calculated by the VS reduction that occurs. The methane percentage also tends to be higher compared to digesters that only receive manure. For example, on Farm ML the average methane content of the biogas is 70%, whereas on Farms AA and NH the average methane content is 62% (see table 3). Little research has been done to explain the effect of food waste on biogas production in manure digesters. Farmers need to be cautious with the amount and types of food wastes they add to manure digesters until these systems are better understood.

Based on the data in tables 1 and 2, the effluent characteristics have less variability than the influent characteristics. The level of fecal coliform in effluent from Farm AA is significantly lower than the rest of the farms, probably because the Farm AA digester has the longest retention time (about double the others). The sampled characteristics in Table 3 are averages and will vary from day to day.

Table 3. Digestion comparisons of five different manure digestion systems.

Farm	AA	DDI	NH	ML	FA
No. of Milking Cows	500	850	1,100	740	100
Digester Type	Plug flow, soft top, manure infeed	Plug flow, soft top, manure infeed	2 parallel Plug flow, hardtop, Manure infeed	Mixed, soft top, manure and food waste infeed	Fixed Film, concrete tank separated liquids infeed
BiogasProductionft^3/cow-day	85	41	64	*[1]	24*[2]
% CO_2 / % Methane	38% / 62%	32% 68%	38% / 62%	30% / 70%	33% / 67%*[2]
Hydraulic Retention Time	40 days	21 days	25 days	21 days*[1]	4 days*[2]
Gas Use	Caterpillar engine generator 130 kW	Capstone microturbines 60 kW*[3]	Caterpillar engine & Marathon generator 130 kW	Waukesha engine & Marathon generator 145 kW	Smith cast iron boilers
Fecal Coliform Reduction (%)	99%	99%	98%	94%	98%*[2]
Effluent Volatile Acids mg/kg	496	1,413	Digester 1 = 520 Digester 2 = 590	386	929*[2]
Total Solids Reduction %*[4]	27	23	24	62	22*[2]
Volatile Solids Reduction (%)	32	23	31	67	26*[2]
Increase in Ammonia (%)	37	27	Digester 1 = 36 Digester 2 = 30	37	11*[2]
Increase in Otho-P (%)	17	13	Digester 1 = 60 Digester 2 = 45	3	15*[2]

*[1] 250,400 ft3/day of biogas was calculated as the average daily production. Since most of the biogas is from food waste, per cow figure is not appropriate.

*[2] For the period 6/2/02 to 4/25/03 when the digester was performing as a fixed film digester. Separated manure liquids only.

*[3] Problems with biogas pre-treatment have resulted in poor performance of the microturbines.

*[4] Reduction in solids from the influent to the effluent of the digester.

Potential pathogen reduction was above 94% for all digesters, and the average was near 99% (table 3). On the other hand, the reduction rate varies for other parameters, generally in accordance with the retention time. Since Farms DDI and NH were both still in a start-up period and had operating issues during the time data was being collected, their performance characteristics are expected to improve. The effluent volatile acid levels in the DDI, NH and FA Farms are above the recommended 500-ppm for odor control. Farm DDI has had a high dilution rate in their raw manure. This increased volume of water has reduced the retention time below the designed value.

There was a shift in the effluent on all farms toward more nitrogen in the ammonia form and more phosphorus in the Ortho-P form; however, the total amounts of N and P remained about the same. These inorganic forms of N and P are more available to plants, and also more easily lost to the environment compared to organic forms. Nutrient management planners can use these results to better plan the rates and timing of manure applications so as to maximize the amount of nutrients available to the plant, and to minimize losses to the environment. Since the odor is reduced, it is possible to apply the effluent closer to planting time, or even during the growing season, without causing odor problems with neighbors. Actively growing plants make the best use of manure nutrients.

Economics

A complete economic analysis is needed for anaerobic digester systems so a producer can make an informed business decision regarding their use. Producers who make a capital investment in an anaerobic digester need to understand the economics of the system; otherwise, they risk making poor investment choices. The capital and estimated operating costs for the five farms are shown in table 4. The available data for the capital costs shown have not been adjusted to reflect the grant funds each farm received.

Table 4. Estimated net income or loss for the five digester systems.

	Farm				
	AA	**DDI**	**NH**	**ML**	**FA**
Number of Cows	500	850	1,100	740	100
Capital Costs					
Digester Set	$192,000	$442,200*[4]	$339,400	$298,149	$80,183
Separator Set	$50,000	$89,000	$61,000	$61,689	$44,013
Gas Utilization Equipment	$61,000	$138,200	$287,300	$130,431	$13,135
Total Capital Cost	$303,000	$669,400	$687,700	$490,269	$137,331
Total Capital Cost Per Cow	$606	$788	$625	$663	$1,373
Annual Projected Capital Cost	$25,468	$52,978	$63,274	$49,016	$13,396
Annual Projected Capital Cost Per Cow	$51	$62	$58	$66	$134
Total Estimated Annual Cost*[1]	$37,540	$79,317	$103,960	$70,880	$21,497
Total Estimated Annual Cost Per Cow*[1]	$75	$93	$95	$96	$215
Total Estimated Annual Revenues	$56,445	$60,400*[3]	$77,680	$287,685	$10,900
Total Estimated Annual Revenues Per Cow	$113	$71*[3]	$71	$389	$109
Total Estimated Annual Cost or Benefit*[1] *[2]	$18,906	-$18,917 *[2] *[3]	-$26,280*[2]	$216,805	-$10,597*[2]
Total Estimated Annual Benefit Per Cow*[1] *[2]	$38	-$22*[2] *[3]	-$24*[2]	$293	-$106*[2]

*[1] Does not include system electrical use.

*[2] Negative numbers mean the farm incurs a net loss from the digester system.

*[3] The electrical savings for DDI assumes the price of electricity is 10 cents/ Kw. This farm actually incurs a lower cost due to a specific business initiative. Since this is not typical of most dairy farms, the higher price is used.

*[4] This cost assumes the microturbines were purchased new.

The values shown for the digester set include capital costs such as the digester structure and cover, influent/effluent, circulate, mixture, and feed pumps, site preparation, biogas boilers, heat exchangers, hot water tanks, and other auxiliary equipment. The separator set includes the capital cost of the separator system, separator building, and interim storage. The gas utilization set includes the capital costs of microturbines, engine/generator sets, switch equipment, the engine building, biogas flare, coolant pumps, heat radiator, solids dryer, electrical engineer consulting fee, any initial rebuild costs, and other gas utilization equipment.

Annual projected capital cost is calculated as the foregone interest, which is estimated to be 5% of the average investment value of the capital plus the annual capital straight-line depreciation. When calculating the annual capital straight-line depreciation, varying useful lives are used according to the expected life of the piece of equipment in the system. The digesters, solid digester covers, buildings, separators, boilers, heat exchangers, microturbines, variable speed drives, and piston pumps are estimated to have a useful life of twenty years. The flexible digester covers, mixing, coolant, and circulating pumps, flares, heat dump radiators, and new engine – generator sets are estimated to have a useful life of ten years. Engine – generator sets that were acquired used, or had to be rebuilt upon purchase, are estimated to have a useful life of seven years. The pH and CO_2 meters, centrifugal, effluent, separator, and food waste feed pumps are estimated to have a useful life of five years. Also, certain components of the system are projected to have a salvage value at the end of their useful life. The salvage value of such equipment is calculated as 10% of the capital cost, or initial investment, for that particular component.

The total estimated annual cost is the sum of the estimated annual capital cost and the estimated annual operating costs. Estimated annual operating costs were estimated based on any annual repairs on the equipment and facilities plus the cost of management, labor, and insurance, but do not include electrical cost to operate the system. Total estimated annual revenues were calculated as an addition of heat savings, electricity savings (only for the non-parasitic power) and sales, profits on solids, tipping fees, bedding, hot water, and composting. They do not include any odor control benefits.

The capital and estimated annual cost and revenue calculations do not include any costs/revenues from manure storage, spreading, or electrical cost to run the system. Manure storage costs, not shown here, varied significantly from farm to farm depending on whether earth, concrete, or metal were used as construction materials. The benefit of being able to use treated manure on cropland previously unavailable for manure use (due to odor problems) was also not considered in this analysis.

Total capital costs vary because each digester is specifically designed for each farm. Farm DDI has microturbines, Farm FA doesn't generate electricity, and the three other farms use engine-generators. Farm AA's capital cost is less than its electricity-generating counterparts because it was built in June of 1998.

The total annual cost or benefit calculation is considered to be the cost the farm pays for odor control when values are less than zero. Farm ML has high earnings because of the annual tipping fee they receive. Total annual cost per cow is not correlated with the total number of cows, again showing that site-specific systems have highly variable costs.

Conclusion

There are a number of different anaerobic digestion configurations that might be appropriate for different farms depending on the farm goals, resources, and situation. Each farm needs to determine the type that works best for them.

There were significant differences in the performance of the digesters. Volatile acids and pathogen reduction varied from digester to digester. Nutrient values seemed to vary less on each farm, as well as between farms.

There were significant differences from farm to farm in the cost of manure systems components.

The addition of food waste increased the amount of methane produced by the anaerobic digester, and dramatically increased the amount of biogas produced.

Anaerobic digesters have a high capital cost and potentially higher annual costs than traditional manure treatment systems. Farms with fewer cows may not be able to afford a digester system because they have fewer animals over which to spread the costs. Grants can offset capital costs for some farms.

Food waste provides the farm with an opportunity to turn manure treatment into a profit center.

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