A Comparison of Dairy Cattle Manure Management with and without Anaerobic Digestion and Biogas Utilization

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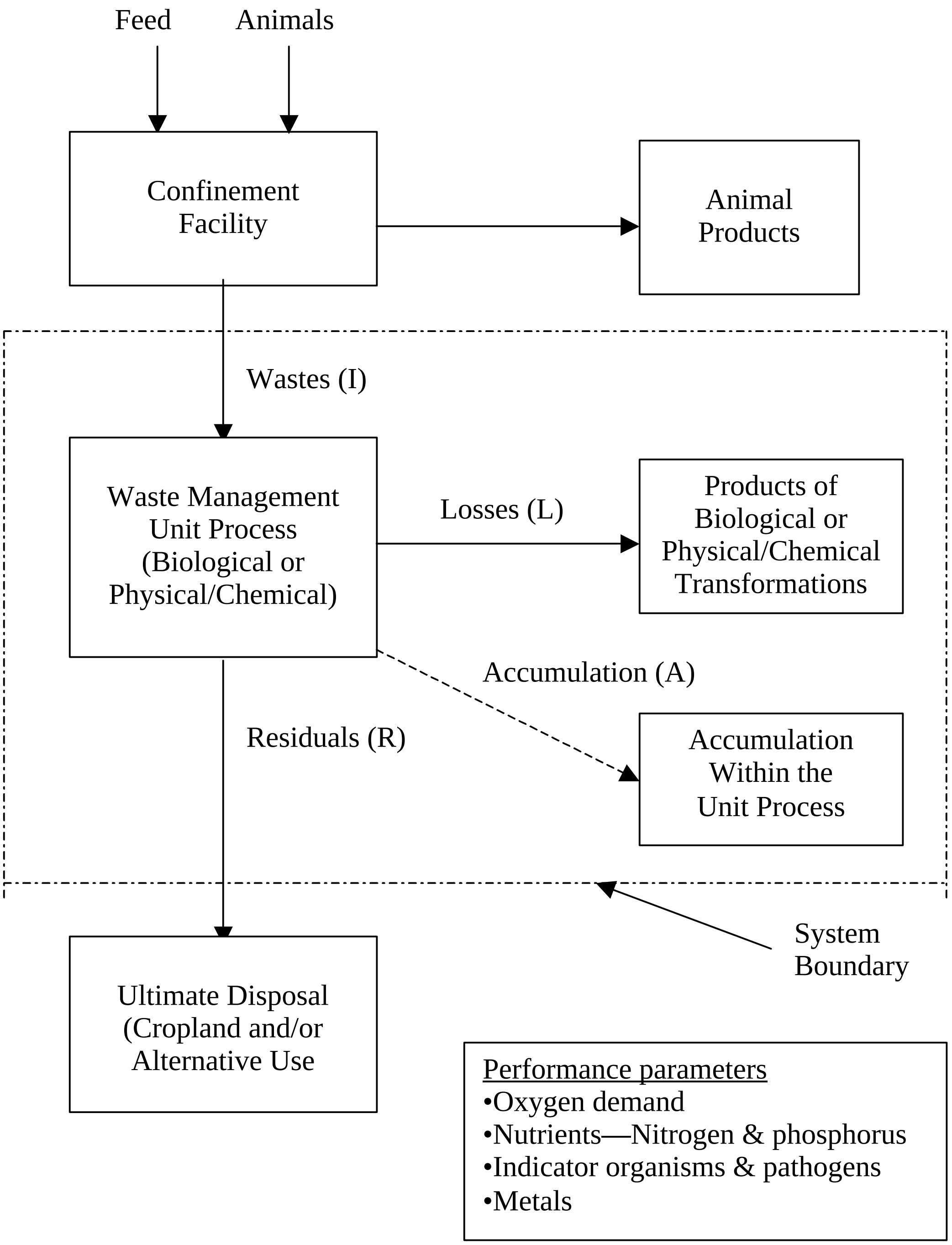
PREFACE

This report summarizes the results from one of a series of studies designed to: 1) more fully characterize and quantify the protection of air and water quality provided by waste management systems currently used in the swine and dairy industries and 2) delineate associated costs. The overall objective of this effort is to develop a better understanding of: 1) the potential of individual system components and combinations of these components to ameliorate the impacts of swine and dairy cattle manures on environmental quality and 2) the relationships between design and operating parameters and the performance of the biological and physical/chemical processes involved. A clear understanding of both is essential for the rational planning and design of these waste management systems. With this information, swine and dairy producers and their engineers as well as the regulatory community will have the ability to identify specific processes or combinations of processes that will effectively address air and water quality problems of concern.

The following schematic illustrates the comprehensive mass balance approach that is being used for each unit process in these performance evaluations. When a system is comprised of more than one unit process, the performance of each process is characterized separately. Then the results are aggregated to characterize overall system performance. This is the same approach commonly used to characterize the performance of domestic and industrial wastewater treatment and chemical manufacturing unit processes. Past characterizations of individual process and systems performance frequently have been narrowly focused and have ignored the generation of side streams of residuals of significance and associated cross media environmental quality impacts. A standardized approach for cost analysis using uniform boundary conditions also is a key component of this comparative effort.



Where: $L = I - (R + A)$
(I and R are measured and
L and A are estimated)

Figure 1. Illustration of a standardized mass balance approach to characterize the performance of animal waste management unit processes.

SECTION 1

SUMMARY AND CONCLUSIONS

The objectives of this study were to compare: 1) the reductions in the potential air and water quality impacts of scraped dairy manure by preceding liquid-solids separation and storage with mesophilic anaerobic digestion in a plug-flow reactor with a flexible geotextile membrane, and 2) the associated cost differential. These reductions and the associated cost differential were determined from characterizations of performance and associated costs for these two dairy manure management strategies on two typical upstate New York dairy farms, AA Dairy and Patterson Farms, Inc. The characterizations of performance were based on materials balances developed for both systems and the cost differential was based on the differential between the cost of anaerobic digestion and the income generated through biogas utilization.

AA Dairy, with an average milking herd of 550 cows, uses anaerobic digestion with biogas utilization to generate electricity, followed by separation of solids, using a screw press separator, in their system of manure management. Patterson Farms also employs solids separation, using a drum type separator, in their manure management system but not anaerobic digestion. Both farms compost separated solids and store the liquid manure remaining after solids separation in earthen storage ponds.

The results of this study provide further confirmation of the environmental quality benefits realized by the anaerobic digestion of dairy cattle manure with biogas collection and utilization for the generation of electricity. These results also confirm that these environmental quality benefits can be realized while concurrently generating revenue adequate to recover capital invested and increase farm net income through the on-site use and sale of electricity generated. In Table 1-1, the impacts of anaerobic digestion on semisolid dairy cattle manure management with solids separation and storage, which are discussed below, are summarized.

Odors

The most readily apparent difference between the AA Dairy and Patterson Farms manure management systems is the effectiveness of anaerobic digestion at AA Dairy in reducing odors. This is the direct result of the degree of waste stabilization provided by anaerobic digestion under controlled conditions. As shown in Table 4-2, average reductions in total volatile solids, chemical oxygen demand, and volatile acids during anaerobic digestion were 29.7, 41.9, and 86.1 percent, respectively. With these reductions, additional degradation during storage under uncontrolled anaerobic conditions and the associated odors are minimized.

Table 1-1. Impacts of anaerobic digestion on a semisolid dairy cattle manure management systems with solids separation and storage.

Parameter	With anaerobic digestion (AA Dairy vs. Patterson Farms)
Odor	Substantial reduction
Greenhouse gas emissions	Methane—substantial reduction (8.16 tons per cow-yr) Nitrous oxide—No evidence of emissions with or without anaerobic digestion
Ammonia emissions	No significant reduction
Potential water quality impacts	Oxygen demand—substantial reduction (8.4 lb per cow-day) Pathogens—substantial reduction (Fecal coliforms: ~99.9%) (*M. avium paratuberculosis*: ~99%) Nutrient enrichment—no reduction
Economic impact	Significant increase in net farm income ($82 per cow-yr)

Greenhouse Gas Emissions

Methane—Perhaps the most significant impact of the anaerobic digestion of dairy cattle manure with biogas capture and utilization is the reduction of the emission of methane, a greenhouse gas with 21 times the heat-trapping capacity of carbon dioxide, to the atmosphere. The reduction in methane emissions, on a carbon dioxide equivalent basis, was determined to be 7.13 tons per cow-year, or 3,924 tons per year for the 550-cow AA Dairy milking herd. If this herd were expanded to the anaerobic digestion-biogas utilization system design value of 1,034 cows, this reduction would increase to 6,076 tons per year. In addition, the electricity generated using biogas has the potential of reducing carbon dioxide emissions from the use of fossil fuels for generating electricity. Under current operating conditions, this reduction is estimated to be 1.03 tons per cow-year and would increase to 1.29 tons per cow-year with herd expansion.

Nitrous Oxide—Analyses of samples of the stored liquid phase of dairy cattle manure after separation at both AA Dairy and Patterson Farms showed that no oxidized forms of nitrogen (nitrite or nitrate nitrogen) were present. Given that conditions required for nitrification, residual concentrations of dissolved oxygen and the absence of inhibitory concentrations of unionized or free ammonia (NH_3), the absence of evidence of nitrification was not surprising. Thus, the expectation of nitrous oxide emissions, as an end product of denitrification, from dairy cattle manure storage structures seemingly has no theoretical basis given the absence of the necessary prerequisite of nitrification.

Other Gaseous Emissions

Analysis of the biogas produced at AA Dairy indicated the presence of only a nominal concentration, 15±5 ppm, of NH_3. The results of this analysis in combination with the total Kjeldahl nitrogen balance results (Table 4-2) indicate the loss of nitrogen via ammonia volatilization during anaerobic digestion of dairy cattle manure is negligible. Thus, it appears reasonable to conclude that ammonia is insignificant as a source of emissions of oxides of nitrogen during biogas combustion. However, the concentration of hydrogen sulfide found in the AA Dairy biogas, 1,930 ppm, indicates that emissions of oxides of sulfur during biogas combustion potentially are significant.

Although anaerobic lagoons used for animal waste stabilization are generally considered significant sources of NH_3, emissions to the atmosphere, the results of this study suggest that at least structures used for the storage of dairy cattle manure are not. For both anaerobically digested and unstabilized manure, nitrogen losses were minimal but somewhat greater (30.2 lbs per cow-year) for the unstabilized manure. However, estimating nitrogen losses from both the AA Dairy and Patterson Farms manure storage structures was confounded by significant spatial variation in total Kjeldahl nitrogen concentrations in both storage structures. Thus, the losses reported in here may be underestimates.

Water Quality Impacts

Oxygen Demand—As mentioned above, the results of data collected at AA Dairy show (Table 4-2) that anaerobic digestion can substantially reduce dairy cattle manure total volatile solids and chemical oxygen demand. These reductions translate directly into a lower potential for depletion of dissolved oxygen in natural waters. Although anaerobically digested dairy cattle manure clearly is not suitable for direct discharge to surface or ground waters, these reductions still are significant due to the potential for these wastes to enter surface waters by nonpoint source transport mechanisms.

Pathogens—As shown in Table 4-4, mesophilic anaerobic digestion at a hydraulic retention time of 34 days was found to provide a mean reduction in the density of members of the fecal coliforms group of enteric bacteria that approached 99.9 percent. For the pathogen, *Mycobacterium avium paratuberculosis*, reduction slightly exceeded 99 percent. *M. avium paratuberculosis* is responsible for paratuberculosis (Johne's disease) in cattle and other ruminants and is suspected to be the causative agent in Crohn's disease, a chronic enteritis in humans. No regrowth of either organism during storage was observed. Thus, it appears that anaerobic digestion of dairy cattle manure also can reduce the potential for the contamination of natural waters by both non-pathogenic and pathogenic microorganisms. . No reductions were observed in the Patterson Farm manure management system.

Nutrient Enrichment—Both nitrogen and phosphorus mass balance results (Table 4-2) demonstrate that anaerobic digestion in a plug flow reactor without the accumulation of settleable solids provides no reduction of the potential impact of these nutrients on water quality.

In addition, results of this study indicate that separation of coarse solids with or without anaerobic digestion only reduces the masses of nitrogen and phosphorus in the remaining liquid fraction by about five percent (Tables 4-9 and 4-14) even though a 17 percent reduction in volume is realized.

Economic Impact

As noted above, the results of this study also confirm that anaerobic digestion with biogas utilization can produce revenue adequate to recover the required capital investment and increase farm net income through the on-site use and sale of electricity generated. Because the AA Dairy anaerobic digester-biogas utilization system was designed for a milking herd of 1,054 cows but currently is being operated with a herd of only 550 cows, the maximum potential of the system to produce biogas and generate electricity currently is not being realized. One of the more significant ramifications of the current operation of this system at less than design capacity is the reduction in the efficiency of the conversion of biogas energy to electrical energy from 30 to 20 percent. Even under these sub-optimal operating conditions, the net income produced by the on-site use and sale of electricity generated is such that the required capital investment can be recovered or repaid in approximately 11 years and then add $32,785 annually to net farm income over the remaining useful life of the system, a period of at least nine years. At the design herd size of 1,034 cows, the capital invested would be recovered in approximately three years and would then add $86,587 annually to net farm income over the remaining useful life of system. Recovery or repayment of the required capital investment over the useful life of the system, estimated conservatively to be 20 years, would somewhat reduce total additions to net farm income but still provide a satisfactory rate of return management and labor. Thus, it can be concluded that there is a significant economic incentive to realize the environmental quality benefits that the anaerobic digestion of dairy cattle manure can provide.

In this study, it was found that anaerobic digestion prior to the separation of course solids does not enhance the separation process or alter the characteristics of the separated solids or the remaining liquid fraction with one notable exception. With anaerobic digestion, the densities of fecal coliforms and *M. avium paratuberculosis* in both fractions were substantially lower.

Therefore, dependence on composting for effective pathogen reduction in the separated solids is lessened.

SECTION 2

INTRODUCTION

Anaerobic digestion is a controlled biological process that can substantially reduce the impact of liquid livestock and poultry manures and manure slurries on air and water quality. Unlike comparable aerobic waste stabilization processes, energy requirements are minimal. In addition, a relatively small fraction of the energy in the biogas produced and captured is adequate to satisfy process needs with the remaining biogas energy available for use as a boiler fuel or to generate electricity. Thus, anaerobic digestion with biogas utilization produces a source of revenue that will at least partially offset process costs and may increase farm net income.

Past interest in anaerobic digestion of livestock and poultry manures was driven primarily by the need for conventional fuel substitutes. For example, interest intensified in France and Germany during and immediately after World War II in response to disruptions in conventional fuel supplies (Tietjen, 1975). This was followed by a renewal of interest in anaerobic digestion of livestock and poultry manures in the mid-1970s stimulated primarily by the OPEC oil embargo of 1973 and the subsequent price increases for crude oil and other fuels. In both instances, this interest dissipated rapidly, however, as supplies of conventional fuels increased and prices declined.

A substantial majority of the anaerobic digesters constructed for biogas production from livestock and poultry manures in the 1970s failed for a variety of reasons. However, the experience gained during this period allowed the refinement of both system design and operating parameters and the demonstration of technical viability.

In the early to mid-1990s, a renewal of interest in anaerobic digestion by livestock and poultry producers occurred. Three primary factors contributed to this renewal of interest. One factor was the need for a cost-effective strategy for reducing manure-related odors from storage facilities, including anaerobic lagoons and land application sites. Another factor was the re-emerging concern about the impacts of livestock and poultry manures on water quality. Finally, the level of concern about global climate change was intensifying and the significance of methane emissions to the atmosphere was receiving increased attention. Recognition of the magnitude of methane emissions resulting from the uncontrolled anaerobic decomposition of livestock and poultry manures led to the creation of the U.S. Environmental Protection Agency’s AgSTAR Program. The primary mission of this program is to encourage the use of anaerobic digestion with biogas collection and utilization in the management of livestock and poultry manures.

Although aerobic digestion also was demonstrated in the 1960s and 1970s to be an effective strategy for controlling odors from and water quality impacts of livestock and poultry manures (Martin and Loehr, 1976 and Martin *et al*., 1981), the cost is prohibitively high due primarily to the electrical energy required for aeration and mixing. In addition, the reduction in methane emissions is at least partially negated by the greenhouse gas emissions associated generation of the electricity required.

Objectives

The objectives of this study were to compare: 1) the reductions in the potential air and water quality impacts of scraped dairy manure by preceding liquid-solids separation and storage with mesophilic anaerobic digestion in a plug-flow reactor, and 2) the associated cost differential. These reductions and the associated cost differential were determined from characterizations of performance and associated costs for these two dairy manure management strategies on two typical upstate New York dairy farms. The characterizations of performance were based on materials balances developed for both systems and the cost differential was based on the differential between the cost of anaerobic digestion and the income generated through biogas utilization.

SECTION 3
METHODS AND MATERIALS

Study Sites

As indicated above, two typical upstate New York dairy farms served as sites for this study. Below is a brief description of each farm and its manure management system.

AA Dairy—AA Dairy is a 2,200-acre dairy farm located in Candor, New York. Candor is in Tioga County, a southern tier county in upstate New York. The AA Dairy milking herd consists, on average, of 550 Holstein-Friesian cows. Average yearly milk production is 23,000 lb per cow. The milking herd is housed in a naturally ventilated free-stall barn, which is connected to a milking parlor.

Manure is removed from the alleys in the free-stall barn daily by scraping into a cross-alley with step dams. In this cross-alley, the manure then moves by gravity to a mixing tank/lift station containing a chopper-type pump for mixing. After mixing, manure is then transferred daily to a mesophilic plug-flow anaerobic digester using a piston pump. After digestion, the coarse solids in the digester effluent are removed mechanically using a FAN screw press separator with the remaining liquid discharged to a 2.4 million-gallon lined earthen storage pond. Both tank wagons and a traveling gun irrigation system are used for application to cropland of manure from the storage lagoon.

The separated solids, consisting primarily of fibrous materials, are transported to a site adjacent to the free-stall barn-milking parlor complex for further stabilization and drying by windrow composting. The finished compost is sold in bulk and bags for use as a soil amendment and mulch material. Approximately 1,825 yd^3 are sold annually at an average of $16 per yd^3.

The plug-flow anaerobic digester was designed and constructed by RCM Digesters, Inc., of Berkley, California, with the expectation of a future herd expansion to 1,054 cows. The digester dimensions are 112 ft long by 28 ft wide by 14 ft deep, and it has an operating volume of 39,568 ft^3. The design hydraulic retention time (HRT) for the digester, based on an expected herd expansion to 1,054 cows, is 24 days with a predicted rate of biogas production of 64,720 ft^3 per day. The digester channel is covered with an impermeable flexible geotextile membrane, which is inflated to a nominal positive pressure by the biogas collected to maintain a semi-rigid surface. The digester has been in operation since mid-1998 and has addressed the odor problems that were the catalyst for considering anaerobic digestion.

Captured biogas is used to fuel a 130 kW engine generator set. The engine, a Caterpillar 3306, is a diesel engine modified by the addition of spark ignition system to use low pressure/low energy biogas as a fuel. The generator is an induction type unit with the following specifications: three phase, 208 volts, and 430 amps at 1,835 rpm. The electricity generated is used to satisfy on-farm demand with any excess energy sold at wholesale rates to the local electric utility, the New York State Electric and Gas (NYSEG) Corporation. Waste heat from the engine cooling system is recovered through a heat exchanger and used to maintain digester temperature at approximately 95 to 98°F. A fuel oil fired hot water boiler is available to maintain digester temperature if the engine-generator set is out of service for maintenance or repairs for an extended period. Biogas produced during such periods is flared to prevent an excessive increase in digester pressure.

<u>Patterson Farms, Inc.</u>—Patterson Farms, Inc. is 1,500-acre dairy farm located in Union Springs, New York. Union Springs is in Cayuga County, a central Finger Lakes county in upstate New York. During this study, the average size of the milking herd increased from 600 to 800 cows. Average yearly milk production is 24,000 lbs per cow. The milking herd is housed in two naturally ventilated free-stall barns, which are connected to a milking parlor.

Manure is removed from the alleys in two free-stall barns daily using alley scrapers, which deposit the scraped manure into a cross alley for transport by gravity into a piston pump reception pit. The manure is then transferred to a holding tank that provides temporary storage before separation of coarse solids. A Houle drum-type separator is used for solids separation with the remaining liquid discharged to a 5.4 million-gallon unlined earthen storage pond. All of the manure from the storage pond is applied to cropland by tank wagon type spreaders. Due to odor problems and the cost of electricity, Patterson Farms is currently is considering the construction of a plug-flow anaerobic digester.

The separated solids, consisting primarily of fibrous materials, are transported by conveyor to a mechanical distribution system in a covered static pile composting facility with forced-air aeration. The finished compost is used as bedding and reduces bedding costs by approximately $60 per cow-year.

Data Collection

The basis for comparing the performance of the two dairy cattle waste management systems evaluated in this study was materials balances developed from measured concentrations of selected parameters in combination with mass flow estimates. At AA Dairy, the following four waste streams; anaerobic digester influent, effluent, and liquid and solid phase effluents from the liquid-solids separation unit; were sampled semi-monthly from late May 2001 through early June 2002. At Patterson Farms, the influent to and the liquid and solid phase effluents from the liquid-solids separation unit also were sampled semi-monthly during the same period. Each sample collected for analysis was a composite of several sub-samples collected over a 15 to 20 minute period of flow to insure that the samples analyzed were representative.

In addition, the storage pond at each farm were sampled at the end of months four, eight, and twelve of the study. For each sampling event, samples were collected at three locations along the axis of the pond perpendicular to the location of the influent discharge. At each location, samples were collected at three depths: the top, middle, and bottom of the liquid column. Each sample was analyzed separately.

As noted earlier, a piston pump is used to initially transfer manure at each farm. This enabled estimation of the volume of manure produced daily by determining the average number of piston strokes per day using a mechanical counter and the manufacturers specification for volume displaced per stroke. The liquid and solid fraction volumes after separation were estimated based the partitioning of total solids between the two fractions assuming conservation of mass through the separation process.

Additional data collection at AA Dairy included volume of biogas utilized and kilowatt-hours (kWh) of electricity generated between days of collection of manure samples. The kWh of biogas-generated electricity used on-site and sold to the local public utility, the NYSEG Corporation, were determined from farm records.

Sample Analyses

Physical and Chemical Parameters—All manure samples collected were analyzed to determine concentrations of the following: total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), soluble chemical oxygen demand (SCOD), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), total phosphorus (TP), orthophosphate phosphorus (PO_4-P), and pH. U.S. Environmental Protection Agency (1983) methods were used for TS, TVS, TKN, TP, PO_4-P, and pH determinations. American Public Health Association (1995) methods were used to determine COD, SCOD, and NH_4-N concentrations. All analyses were performed by an analytical laboratory certified by the New York State Department of Environmental Conservation.

Biodegradability—A 55-day batch study was conducted to estimate the biodegradable and refractory fractions of TVS in a random sample of as excreted manure from AA Dairy. The study was a laboratory scale study in which two liters of AA Dairy manure was maintained at 95 °F (35 °C) in a glass reactor. A water trap was used to vent the biogas produced and maintain anaerobic conditions in the reactor. The contents of the reactor were sampled and analyzed to determine TVS on days 0, 7, 10, 15, 30, and 55 of the batch study.

Microbial Parameters—Two parameters were used to characterize the fate and transport of indicator and pathogenic microorganisms in the AA Dairy and the Patterson Farms waste management systems. One parameter was the fecal coliform group of bacteria (fecal coliforms), a group of bacteria that includes *Escherichia coli*, *Klebsiella pneumoniae,* and other species, which are common inhabitants of the gastro-intestinal tract of all warm-blooded animals. The presence of fecal coliforms is commonly used as an indicator of fecal contamination and the possible presence of pathogenic microorganisms. In addition, a reduction in fecal coliform density serves as an indicator of reductions in the densities of pathogenic microorganisms. Densities of fecal coliforms were estimated using the multiple tube fermentation technique (American Public Health Association, 1995) by the same laboratory that performed determinations of physical and chemical characteristics.

The second microbial parameter was the pathogen *Mycobacterium avium paratuberculosis*, which is the microorganism responsible for paratuberculosis (Johne's disease) in cattle and other ruminants. Paratuberculosis is a chronic, contagious enteritis characterized eventually by death. *M. avium paratuberculosis*, formerly known as *M. paratuberculosis* or *M. johnei*, is also suspected to possibly be the causative agent in Crohn's disease, a chronic enteritis in humans (Merck and Company, Inc., 1998). Thus, *M. avium paratuberculosis* is considered a possible zoonotic risk. Determinations of densities of *M. avium paratuberculosis* were performed by the New York Animal Health Diagnostic Laboratory, Cornell University College of Veterinary Medicine using the "Cornell Method," which has been described by Stabel (1997). Although Stabel reported the Cornell Method to be less sensitive than other methods, it satisfies the requirements of the U.S. Department of Agriculture (USDA) National Veterinary Services Laboratory proficiency-testing program.

Biogas Composition—A random sample of AA Dairy biogas was analyzed by gas chromatography using ASTM Method D1946 (ASTM International, 1990) to determine methane and carbon dioxide content. The same sample was analyzed using EPA Method 16 to determine hydrogen sulfide content and using Sensidyne ammonia detection tubes to determine ammonia (NH_3) content.

Data Analysis

Each data set generated in this study was analyzed statistically for the possible presence of extreme observations or outliers using Dixon's criteria for testing extreme observations in a single sample (Snedecor and Cochran, 1980). If the probability of the occurrence of a suspect observation based on order statistics was less than five percent ($P<0.05$), the suspect observation was considered an outlier and not included in subsequent statistical analyses.

With the exception of bacterial densities, all data sets were found to be approximately normally distributed and the null hypothesis that two means do not differ significantly ($P<0.01$) was tested using the Student's *t* test. For multiple comparisons, one-way analysis of variance (ANOVA) was used. If the null hypothesis that the means do not differ significantly ($P<0.01$) was rejected, Tukey's Honest Significance Test for pairwise comparisons of means (Steel and Torrie, 1980) was used. To equalize variances, densities of fecal coliform bacteria and *Mycobacterium avium* *paratuberculosis* were transformed logarithmically before calculation of means and standard deviations and comparisons of means to determine the statistical significance of differences. A $\log_{10}$ (Y+1) transformation was used because the presence of *M. avium paratuberculosis* was not always detected.

The procedure used to estimate the biodegradable and refractory fractions of TVS in as excreted AA Dairy manure from the results of the batch biodegradability study is based on the assumption that the biodegradable fraction of TVS approaches zero as the solids retention time (SRT) approaches infinity. Therefore, the refractory fraction of TVS can be determined graphically by plotting a time series of ratios of TVS concentrations to the initial TVS concentration versus the inverse products of the initial TVS concentration and the corresponding unit of time. The resulting relationship should be linear with the ordinate axis intercept representing the refractory fraction of TVS.

SECTION 4

RESULTS

AA Dairy

Manure Production and Characteristics—As shown in Table 4-1, the volume of manure produced per cow-day at the AA Dairy is somewhat higher than the standard reference values proposed by the American Society of Agricultural Engineers (2001) and the U.S. Department of Agriculture (1992). However, both the American Society of Agricultural Engineers (ASAE) and the USDA estimates are as excreted values. Thus, they do not include any water used for cleaning or accidental spillage from drinkers, which are included in the AA Dairy value.

Generally, the AA Dairy manure characteristics, on a kg per cow-day basis, are within the ranges of the ASAE and USDA values suggesting any dilution is minimal. COD is, however, the one notable exception. The reason or reasons for the substantially higher AA Dairy value are unclear but may reflect differences in feeding practices or differences in analytical precision and accuracy. Because of the presence of particulate matter in a variety of sizes (undigested fiber) in dairy cow manure and the degree of sample dilution necessary prior to COD determination, obtaining a representative subsample, even after sample homogenization, is a difficult process. Finally, the absence of significant differences in rates of excretion of TKN and total TP between the AA Dairy and the standard reference values is noteworthy.

Digester Operating Conditions—Based on manure production rate of 2.1 ft^3 per cow-day and the herd size of 550 cows, the HRT of the AA Dairy anaerobic digester as operated during this study was 34 days. This is 10 days longer than the design HRT of 24 days, which was based on planned expansion of the herd size of 1,054 cows. If future herd expansion to 1,054 cows does occur, the digester HRT will be reduced to approximately 18 days, which is 75 percent of the design HRT.

Waste Stabilization—An assessment of the AA Dairy plug-flow anaerobic digester performance, based on comparisons of mean influent and effluent concentrations, is presented in Table 4-2. As shown, there were substantial and statistically significant ($P<0.01$) reductions in TS, TVS, COD, SCOD, and TVA. Conversely, concentrations of NH_4-N and PO_4-P increased while there were no statistically significant differences between influent and effluent concentrations of fixed solids (FS), TKN, organic nitrogen (ON), and TP. The lack of significant differences between influent and effluent concentrations of FS and TP indicate that this digester is operating in an ideal plug-flow mode with no accumulation of total solids and related parameters occurring. The one anomaly in these data is the absence of a statistically significant reduction in ON concentration comparable to the increase in the concentration of NH_4-N. The reason for this anomaly is not clear, but the lack of a statistically significant difference between influent and effluent TKN concentrations indicates that nitrogen loss through desorption of NH_4-N in the digester is at most minimal. The differences between influent and effluent concentrations of TVS and COD (Table 4-2) translate into the mass reductions presented in Table 4-3. It should be noted that the mass reductions in TS and TVS essentially are the same providing further evidence of the validity of the data set.

Biodegradability—The results of the batch study to estimate AA Dairy manure TVS biodegradability indicate that 30 percent of the TVS are readily biodegradable and 70 percent are refractory.

Indicator Organism and Pathogen Reduction—As shown in Table 4-4, the $\log_{10}$ densities of both the fecal coliform group of bacteria and *M. avium paratuberculosis* were reduced substantially in the AA Dairy anaerobic digester. On a colony-forming unit (CFU) per g of manure basis, the reduction in the density of fecal coliforms was almost 99.9 percent while the reduction in *M. avium paratuberculosis* density was slightly greater than 99 percent.

Biogas Production—As described earlier, AA Dairy uses the biogas produced to generate electricity with waste heat from the engine-generator set used to heat the digester. When the engine-generator set is out of service, biogas is flared and a fuel oil-fired hot water boiler is used to maintain digester temperature. Only the biogas utilized to fuel the engine-generator set is metered. During this study, this meter failed in late November 2001 and was not replaced until early January 2002. This failure resulted in the loss of a little over two months of biogas production data. This failure was followed by an engine-generator set controller problem resulting in the unit being shut down from January through March 2002. However, resolution of this problem by installing a new controller with a cumulative kWh meter also resolved the problem of accurately determining cumulative engine-generator set electrical output. Originally, it was planned to acquire and install a commercial type kilowatt-hour meter at the beginning of the study to obtain this information. It was found, however, purchases of these meters from manufacturers now are limited to public utilities, and the local public utility, the NYSEG Corporation, was unable to locate a suitable reconditioned meter.

Because of the gas meter failure followed by the failure of the engine-generator set failure, determination of biogas production from late November 2001 through early April 2002 was not possible. Thus, there were two separate periods for which biogas production was determined. For the period of the study prior to the gas meter and engine-generator set controller problems (21 May through 26 November 2001), biogas production averaged 38,907 ± 13,386 ft^3 per day. For the period of the study after the resolution of the gas meter and engine-generator set controller problems discussed earlier (2 April through 17 June 2002), biogas production was 42,868 ± 3,144 ft^3 per day. Although the difference between these two periods in average daily biogas production is relatively small, the accuracy of the biogas production estimate for the 21 May through 26 November time is suspect because of a high degree of daily variability. The coefficient of variation for this period was approximately 34 percent, probably reflecting the gradual failure of the gas meter that eventually was replaced. In contrast, variability in daily biogas production for the period after gas meter replacement was only approximately seven percent. Therefore, it seems reasonable to conclude that the estimate of average daily biogas production of 42,868 ft^3 based on data collected from 2 April through 17 June 2002 is the more accurate estimate of biogas production at AA Dairy. This translates into a rate of biogas production of 78 ft^3 per cow-day, which is 28 percent higher than the originally anticipated rate of biogas production of 61 ft^3 per cow-day based on a herd size of 1,054 cows.

Previously, the methane content of the biogas produced by the AA Dairy anaerobic digester has been reported to vary between 50 to 55 percent with a variation in hydrogen sulfide content from 0.1 to 0.36 percent (Peranginangin and Scott, 2002). Results (Table 4-5) of the analysis of a random sample of the AA Dairy biogas indicated a slightly higher methane content of 59.1 percent. The concentration of hydrogen sulfide in that sample was 1,930 ppm. The NH_3. concentration, based on five replicate determinations, was found to be 15±5 parts per million, confirming the conclusion, based on mass balance results, that NH_3 desorption during anaerobic digestion is nominal.

Based on a methane content of 59.1 percent (Table 4-5) and the previously discussed rate of biogas production of 42,868 ft^3 per day, the rate of methane production by the AA Dairy anaerobic digester is 25,335 ft^3 per day. Theoretically, the destruction of one lb of ultimate biochemical oxygen demand (BOD_u) under anaerobic conditions should result in the generation of 5.62 ft^3 of methane (Metcalf and Eddy, 1991). Although not all COD is biodegradable, it can be assumed that a microbially mediated reduction of COD is equal to a reduction of the same magnitude in BOD_u. Thus, the 41.9 percent reduction in COD in the AA Dairy anaerobic digester (Table 4-2) is equivalent to a 4,641 lb per day (Table 4-3) reduction in BOD_u. As shown in Table 4-6, this translates into a rate of methane production of 5.46 ft^3 per lb of COD destroyed, which is slightly more than 97 percent of the theoretical value. Based on the ratio COD to TVS destroyed of 2.25 (Table 4-3), 12.64 ft^3 of methane should have been produced per lb of TVS destroyed. Thus, observed value of 12.30 ft^3 of methane produced per lb of TVS destroyed also compares favorably with the theoretical value. Anaerobic digestion of municipal wastewater treatment sludges (biosolids) typically yields between 12 and 18 ft^3 of methane per lb TVS destroyed (Metcalf and Eddy, Inc., 1991).

Biogas Utilization—For the period 2 April through 17 June 2002, 1,433±133 kWh of electricity was generated daily. The on-line efficiency of the engine-generator set during this time period was 96.8 percent and 33.29 ± 1.13 kWh were generated per 1,000 ft^3 of biogas utilized. The validity of this estimate of electricity was confirmed by the subsequent determination that the rate of electricity generation for the 180-day period from 2 April though 30 September 2002 was 1,429 kWh per day with an on-line efficiency of 98.8 percent. Thus, only about 20 percent of biogas energy is being recovered as electrical energy. This low conversion efficiency is probably is the result of the utilization of somewhat less than 50 percent of the engine-generator set's rated capacity of 130 kW. At full load, conversion of biogas energy to electrical energy should approach 30 percent with the added potential of recovering up to 60 percent of biogas energy as heat energy (Koelsch and Walker, 1981).

Solids Separation—As mentioned earlier, AA Dairy uses a screw press separator to recover coarse solids from the digester effluent for sale after composting as a mulch material or soil amendment. On a volume basis, 196 ft^3 of separated solids are generated daily, which reduces the digester effluent flow to the storage pond by approximately 17 percent. In Table 4-7, the characteristics of the digester effluent and the separated liquid and solid fractions are compared.

As indicated in Table 4-7, the digester effluent, separated liquid, and separated solid concentrations of TS, TVS, FS, and COD differ significantly ($P<0.01$) from each other, whereas there are no statistically significant differences in SCOD, TKN, NH_4-N, and PO_4-P concentrations. For ON, there is no statistically significant difference between the digester effluent (separator influent) and the separated liquid and separated solids concentrations. However, the difference between the separated liquid and separated solids concentrations is significant statistically indicating the concentration of ON in the separated solids. For TP, the digester effluent and separated liquid concentrations are not significantly different statistically but the differences between these concentrations and the concentration in the separated solids fraction is significant statistically. This is probably a reflection of the concentration of the organic fraction of TP in the separated solids.

As shown in Table 4-8, the digester effluent and separated liquid densities of fecal coliforms and *M. avium paratuberculosis* are not significantly different statistically ($P<0.01$), but the digester effluent and separated solids densities do differ significantly. However, there are no statistically significant differences in separated liquid and separated solids densities. Therefore, it only can be concluded that separation provides no statistically significant reductions in fecal coliform and *M. avium paratuberculosis* densities as would be expected.

As indicated earlier, the solids separated from the AA Dairy digester effluent represent about 17 percent of the digester effluent volume with the liquid fraction remaining after separation constituting the remaining 83 percent. As shown in Table 4-9, the separated solids, on a mass basis, also contain 17 percent of the TS and TVS present before separation with the remaining 83 percent in the liquid fraction. The partitioning of COD is similar to that of TS and TVS. However, the separated solids contain only about five percent of the nitrogen and phosphorus present before separation.

As previously mentioned, the separated solids at the AA Dairy are composted for further stabilization prior to sale as a mulch material or soil amendment. Assuming that the organic carbon content of the separated solids can be estimated with a reasonable degree of accuracy as approximately 55.5 percent of TVS (Haug, 1980 and Rynk *et al*., 1992), the carbon to nitrogen (C:N) ratio of the AA Dairy separated solids is approximately 23:1. At this C:N ratio, nitrogen availability will not limit the rate of stabilization but some nitrogen loss through NH_3-N volatilization should occur. A C:N ratio of 30 to 35:1 generally is considered optimal for minimizing nitrogen loss without limiting the rate of stabilization.

<u>Storage Pond Transformations</u>—As mentioned earlier, the AA Dairy earthen structure used to store the liquid fraction of the digester effluent after separation was sampled at the end of months four, eight, and twelve of this study. The results of the analyses of these samples showed significant variation in concentrations of both physical and chemical parameters with depth and to a lesser degree with location relative to the point of influent discharge to the storage structure. To provide a general characterization of the contents of the storage structure, a mean value was calculated for each parameter that was calculated for each sampling event. Then, mean values were calculated from the mean values for each sampling event. The results of these calculations are compared to the characteristics of the storage pond influent (separator liquid phase effluent) in Table 4-10. As shown, there are substantial differences in the concentrations of all of the parameters listed between storage pond influent and the pond contents. Because there is no microbial or physical/chemical process that could cause the loss of TP, it is apparent that significant dilution is occurring in this storage pond. To adjust for the effect of dilution, each storage pond influent concentration was multiplied by the ratio of storage pond influent TP concentration to the storage pond TP concentration. Based on these transformations, it appears that only minimal reductions in TS and TVS and no reduction in COD are occurring. Nitrogen loss also appears to be minimal and translates into a loss of about 5.5 lbs per cow-year.

Patterson Farms, Inc.

<u>Manure Production and Characteristics</u>—As shown in Table 4-11, the volume of manure produced per cow-day at Patterson Farms also is somewhat higher than the standard reference values proposed by the ASAE (2001) and the USDA (1992). However, the Patterson Farms

manure characteristics, on a kg per cow-day basis, also are within the ranges of the ASAE and USDA values with COD again being the one notable exception. The reason or reasons for the substantially higher Patterson Farm value are unclear but again may reflect differences in feeding practices or differences in analytical precision and accuracy for the reasons discussed earlier. The somewhat lower PO_4-P value is noteworthy but does not appear to be significant.

Solids Separation— As noted earlier, Patterson Farms uses a drum-type separator to remove the coarse solids fraction from their manure for use as a bedding material after composting. On a volume basis, about 38 ft^3 of separated solids per 100 cows are generated daily, which reduces manure storage requirements by approximately 16 percent. In Table 4-12, the characteristics of the digester effluent and the separated liquid and solid fractions are compared. As indicated, the separator influent, separated liquid, and separated solid concentrations of TS, TVS, and COD differ significantly ($P<0.01$) from each other, whereas there are no statistically significant differences in, TKN, ON, TP, and PO_4-P concentrations. For SCOD and NH_4-N, separator influent and separated liquid concentrations did not differ significantly, but separated solids concentrations were significantly but not substantially lower.

As shown in Table 4-13, fecal coliform densities in separator influent and separated liquid and solids do not differ significantly ($P<0.01$). However, separation appears to significantly reduce the density of *M. avium paratuberculosis* with mean separated liquid and solids densities approximately one $\log_{10}$ (90 percent) lower than the mean influent density. Given that there was no observed reduction in fecal coliform density, it is not clear what mechanism or mechanisms could be responsible for the reduction in *M. avium paratuberculosis* density. However, it may be some function the higher influent density, 4.00±0.48 $\log_{10}$ CFU per gram, versus 1.94±0.62 CFU $\log_{10}$ per gram in the separator influent at AA Dairy.

As indicated earlier, the solids separated from Patterson Farms manure represent about 16 percent of the volume of manure produced daily. As shown in Table 4-14, the separated solids, on a mass basis, also contain 16 percent of the TS and TVS present before separation with the remaining 84 percent in the liquid fraction. The partitioning of COD is similar to that of TS and TVS. However, the separated solids contain only about six percent of the nitrogen and four percent of the phosphorus present before separation, which is similar to the AA Dairy partitioning values (Table 4-9).

As discussed earlier, the separated solids at Patterson Farms are used after stabilization by composting. The C:N ratio of the separated solids of 32:1 suggests that nitrogen availability should not limit the rate of stabilization and nitrogen loss via NH_3 volatilization should be minimal.

Storage Pond Transformations—The earthen structure used to store the liquid fraction of the separator effluent also was sampled at the end of months four, eight, and twelve of this study. The results of the analyses of these samples also showed significant variation in concentrations of both physical and chemical parameters with depth, and to a lesser degree, with location relative to the point of influent discharge to the storage structure. Using the same approach described above for the AA Dairy storage pond, mean values to characterize the storage pond contents were calculated. The results of these calculations are compared to the characteristics of the storage pond influent (separator liquid phase effluent) in Table 4-15. As shown, there are some differences in the concentrations of all of the parameters listed between storage pond influent and the pond contents. However, the difference between the TP concentrations in the storage pond influent and contents is significantly less than that for the AA Dairy storage pond, indicating much less dilution for reasons that are not clear. However, the storage pond influent concentrations also were adjusted using the previously described approach to provide for direct comparisons.

Based on these transformations, it appears again that only minimal reductions in TS and TVS and no reduction in COD are occurring. However, nitrogen loss is greater than that from the AA Dairy storage pond and translates into a loss of about 29.5 lbs per cow-year but is only approximately six percent of the nitrogen excreted. It should be noted that the densities of fecal coliforms and *M. avium paratuberculosis* in the storage pond influent adjusted for dilution and the storage pond contents are essentially the same. This suggests that storage provides no reduction in pathogen densities.

SECTION 5

DISCUSSION

Manure Production and Characteristics

As shown in Table 5-1, there is little difference between AA Dairy and Patterson Farms rates of production of manure and its various constituents. In addition, there is little difference, as previously discussed, between these rates and the standard reference values published by the ASAE (2001) USDA (1992). This suggests that the two farms involved in this study are representative of typical U.S. dairy operations with respect to rates of production of manure and its various constituents. In addition, there is little difference between the AA Dairy and Patterson Farms in raw manure concentrations of solids, COD, nitrogen, and phosphorus (Table 5-2).

AA Dairy Anaerobic Digester Performance and Biogas Utilization

<u>Waste Stabilization</u>—As indicted earlier, the AA Dairy plug-flow anaerobic digester was designed to operate at a HRT of 24 days but operated at a HRT of 34 days during this study because the anticipated herd expansion from 550 to 1,054 cows has not yet occurred. At this HRT, TVS and COD reductions averaged 29.7 and 41.9 percent, respectively (Table 4-2). The 29.7 percent reduction in TVS observed in this study is significantly lower than the reduction reported by Morris (1976) of 37.6 percent at a HRT of 30 days in a bench-scale anaerobic digester. However, the 41.9 percent reduction in COD is essentially the same as the 40.6 percent reduction reported by Morris. The 29.7 percent reduction in TVS observed in this study also is significantly lower than the reduction reported by Jewell *et al*. (1991) for a 65-cow plug-flow digester of 40.6 percent at a HRT of 30 days. However, Jewell *et al*. also reported a TVS reduction of 31.7 percent in a 65-cow completely mixed digester operated at the same HRT. A possible explanation for this difference between the plug-flow and the completely mixed digester in TVS reduction is that the plug-flow digester was not operating in an ideal plug-flow mode and accumulation of settleable solids in the digester was occurring. The approximately 10 percent higher rates of biogas and methane production per unit of TVS destroyed in the completely mixed digester provide some support for the validity of this hypothesis. Thus, the 29.7 percent reduction of TVS observed in this study does seems reasonable and may simply reflect

differences in dairy cattle feeding programs. The lack of statistically significant differences in influent and effluent concentrations of FS and TP (Table 4-2) suggests that such accumulation was not occurring in the AA Dairy digester during this study.

The results of the batch biodegradability study indicate that 30 percent of AA Dairy manure TVS are readily biodegradable with the remaining 70 percent being refractory. Thus, it appears that essentially all (99.0 percent) of the biodegradable volatile solids (BVS) in AA Dairy manure are being degraded at the digester HRT of 34 days. The linear regression relationship developed from the batch biodegradability data (Equation 1) also suggests that reducing digester HRT to the design value of 24 days would reduce TVS reduction from 29.7 to 26.0 percent and BVS reduction to 86.7 percent. Therefore, increasing herd size to the design value of 1,054 cows would only marginally reduce the degree of waste stabilization.

$$TVS_t/TVS_0 = 0.12\ (1/TVS_0 * t) + 0.70 \qquad (1)$$

where: TVS_t = total volatile solids concentration at time t,
TVS_0 = total volatile solids concentration at time 0,
t = time (SRT).

Pathogen Reduction—Given that paratuberculosis is a major problem in the dairy industry with transmission by fecal-oral contact and the possibility that *M. avium paratuberculosis* is the pathogen responsible for the development of Crohn's disease in humans, the 99 percent reduction in the density of this pathogen during anaerobic digestion is highly significant. In addition, the 99.9 percent reduction in the density of fecal coliforms suggests that significant reductions in other pathogens also are possible. The impact of a reduction in digester HRT from 34 to 18 days on fecal coliforms and *M. avium paratuberculosis* reductions is less clear. However, it is probable that some decrease in the reductions of the densities of these microorganisms could occur.

Biogas Production—As noted earlier, the mean rate of biogas production observed in this study was 78 ft^3 per cow-day, which is 28 percent higher than the design value of 61 ft^3 per cow-day for the anticipated herd size of 1,054 cows and a digester HRT of 24 days. However, the rate of manure production for AA Dairy of 2.10 ft^3 per cow-day determined in this study would result in an HRT of only 18 days if herd expansion to the design value of 1,054 cows occurs in the future. While it is probable that some reduction in TVS and COD reduction and biogas production per cow-day would occur, the work of Morris (1976) and Jewell *et al*. (1991) suggests that any reductions should be minimal. Morris reported a slight decrease in TVS reduction from 37.6 to 35.1 percent when HRT was reduced from 30 to 20 days. He also reported that COD reduction increased, which probably was an anomaly, from 40.6 to 42.9 percent. If these TVS and COD reductions at 20 and 30 day HRTs could be compared statistically, it is probable that there would be no significant differences. In addition, Jewell *et al*. reported only nominal decreases in TVS reductions in both a plug-flow and completely mixed digester as HRTs were reduced from 30 to 15 days. The reductions for the plug-flow and completely mixed digester were respectively from 40.6 to 34.1 percent and from 31.7 to 27.8 percent.

Based on the linear regression relationship derived from the batch biodegradability study (Equation 1), a reduction in the HRT of the AA Dairy plug-flow digester from 34 to 18 days would reduce TVS reduction from 29.7 to 24.0 percent. This translates into a reduction in biogas production from 78 ft^3 to approximately 63 ft^3 per cow-day, which is close to the original design value of 61 ft^3 per cow-day noted above. However, it also would result in an increase in the daily rate of biogas production from 42,868 ft^3 per day for 550 cows to 63,840 ft^3 per day for the design herd size of 1,054 cows.

Biogas Utilization—As previously discussed, less than 50 percent of the AA Dairy engine-generator set capacity for the conversion of biogas energy to electrical energy currently is being utilized. Thus, the efficiency of conversion of biogas energy to electrical energy is only about 20 percent as opposed to a potential conversion efficiency approaching 30 percent if the 130 kW engine-generator set was being operated at or near full load. An increase in conversion efficiency from 20 to 30 percent would increase the kWh of electricity generated per 1,000 ft^3 of biogas from 33.29 to 49.94 kWh. Therefore, the anaerobic digestion-biogas utilization infrastructure currently in place at AA Dairy has the capacity with the design herd size of 1,054 cow of generating 3,315 kWh of electricity per day. This estimate is conditioned on the validity of the previously stated assumption that biogas production per cow-day only would decrease from 78 to 63 ft^3 per cow-day with a reduction of digester HRT from 34 to 18 days.

Methane Emissions—At the observed rate of methane production by the AA Dairy digester of 25,335 ft^3 per day, 9,247,275 ft^3 of methane per year is being captured and utilized to generate electricity. Because methane has 21 times the heat trapping capacity of carbon dioxide (U.S. Environmental Protection Agency, 2002), the reduction in methane emission being realized is equal to a reduction in the emission of an equivalent of 4,120 tons of carbon dioxide per year or 7.49 tons per cow-year. Although carbon dioxide emissions do occur with methane combustion, this only decreases the impact of the reduction in methane emissions by roughly five percent or 206 tons per year. Therefore, the net reduction in methane emission on a carbon dioxide equivalent basis is 3,924 tons per year or 7.13 tons per cow-year. At the design herd size of 1,054 cows, the net reduction in methane emission on a carbon dioxide equivalent basis would be 6,076 tons per year.

However, the reduction in greenhouse gas emissions due to biogas production and utilization at AA Dairy is not limited to the reduction in methane emissions. The use of the biogas produced and captured to generate electricity reduces the demand for electricity generated using fossil fuels. Thus, carbon dioxide emissions resulting from the use of fossil fuels to generate electricity also are reduced. Assuming 2,249 lbs of carbon dioxide are emitted per megawatt-hour (MWh) of electricity generated from coal (Spath *et al*., 1999), the estimated 501,510 kWh of electricity generated annually by AA Dairy using biogas potentially reduces fossil fuel derived carbon dioxide emissions by an additional 564 tons per year or 1.03 tons per cow-year. At the design herd size of 1,054 cows, the reduction in fossil fuel derived carbon dioxide emissions would be an additional 1,361 tons per year or 1.29 tons per cow-year.

Therefore, the current total reduction in greenhouse gas emissions, on a carbon dioxide equivalent basis, is 4,488 tons per year or 8.16 tons per cow-year. The potential reduction at the design herd size of 1,054 cows would be 7,437 tons per year or 7.06 tons per cow-year. In this analysis, the emission during combustion of the carbon dioxide component of biogas is not considered since it is not a carbon dioxide emission derived from a sequestered carbon source. Rather, it is an emission that is part of the natural short-term carbon cycle where carbon dioxide is fixed by photosynthesis and then is regenerated as the plant matter produced is degraded microbially and by higher animals.

Nitrous Oxide Emissions—The results of analyses of samples of the stored liquid phase of dairy cattle manure after separation at both AA Dairy and Patterson Farms showed that no oxidized forms of nitrogen (nitrite or nitrate nitrogen) were present. This finding was not surprising given the absence of residual dissolved oxygen concentrations required for nitrification and the high unionized ammonia (NH_3.)concentrations, which inhibits nitrification, in both storage structures. Thus, the expectation of nitrous oxide emissions, as an end product of denitrification, from dairy cattle manure storage structures seemingly has no theoretical basis given the absence of the necessary prerequisite of nitrification. In addition, any nitrite or nitrate nitrogen, which is rarely present in dairy cattle manure when excreted, would be denitrified before storage due the high level of carbonaceous oxygen demand in these wastes.

Separator Performance

As discussed earlier, AA Dairy uses a screw press separator to separate coarse solids from the effluent from the anaerobic digester while Patterson Farms uses a drum-type unit to remove coarse solids from raw manure before storage of the separated liquid fraction. Due to the anaerobic digestion prior to solids separation, the influent to the AA Dairy separator has substantially lower concentrations of solids and COD than the influent to the Patterson Farm's separator. Thus, an expectation that the efficiency of separation would differ would be reasonable. However, the distribution of influent constituents between liquid and solid phases after separation was remarkably similar as shown previously in Tables 9 and 13. In addition, there was little difference between the two farms in the characteristics of the separated solids with the exception of concentrations of nitrogen and phosphorus and densities of fecal coliforms and *M. avium paratuberculosis* (Table 5-3). In contrast, there were significant differences in the characteristics of the separated liquids (Table 5-4). Generally, these differences were reflections of the differences in separator influent characteristics (Tables 7 and 11). The similarities in the characteristics of the AA Dairy and Patterson Farms separated solids (Table 5-3) as well the distributions of the influent constituents between liquid and solid phases (Tables 9 and 13) suggest that anaerobic digestion of dairy manure prior to separation neither enhances nor negatively impacts the efficiency of separation. However, qualification of this conclusion is necessary because it is based on the assumption that the efficiencies of screw press and drum-type separators are equal.

Storage Pond Transformations

Based on comparisons of the physical, chemical, and microbiological characteristics of the influents to and the contents of the AA Dairy and Patterson Farms storage ponds (Tables 10 and 15), there is no evidence of any significant transformations occurring in either structure. With respect to reductions in TS, TVS, and COD, this finding is not entirely surprising given that these structures are designed for solely for storage. If designed as an anaerobic lagoon with the objective of waste stabilization following the USDA (1992) suggested TVS loading rate for central New York State, a structure with approximately six times the volume of the AA dairy storage pond would be required. The Patterson Farms structure would have to be approximately four times larger. Therefore, it seems reasonable to conclude, with the following caveat, that the lack of significant reductions in TS, TVS, and COD are reflections of the absence of conditions suitable for anaerobic waste stabilization processes. The comparisons of characteristics of the influents to and the contents of both storage ponds may have been unintentionally biased, however, by the schedule for storage pond sampling. The first sampling events where in October following reductions in stored manure volume to provide adequate storage capacity through early spring. Therefore, the characteristics of these sets samples did not necessarily reflect transformations that occurred during warm weather when microbial activity would have been highest. In addition, the second set of samples from each storage structure was collected in January and the third set was collected in early April. Thus, the results obtained may have been unintentionally biased by not proportionally reflecting the effect of low temperature on microbial activity.

It was expected that there would be a significant loss of nitrogen as the result of NH_3. volatilization from both storage structures given the influent NH_4-N concentrations (Tables 10 and 15). However, there appear to be at least two factors contributing to the lack of any significant NH_3. volatilization from either storage pond. In the contents of both storage ponds, NH_4-N concentrations increased as TS concentrations increased with depth. This indicates sorption of NH_4-N to particulate matter was significant and thereby limited the potential for nitrogen loss by NH_3. volatilization. In addition, mean pH values for both storage ponds (Tables 10 and 15) were near neutral, which also limited the potential for NH_3. volatilization. The sampling schedule discussed above also may have unintentionally biased the estimations of nitrogen losses because NH_3. volatilization potential also decreases with temperature.

The results from this phase of the study do demonstrate, however, that storage does not provide significant reductions in fecal coliform or *M. avium paratuberculosis* densities. This finding is further evidence of the merit of anaerobic digestion as a component of dairy cattle manure management systems.

Economic Analysis

Introduction—One of the objectives of this study was to quantify the impact of anaerobic digestion with biogas capture and utilization to generate electricity on the cost of dairy cattle manure management. In previous cost analyses of anaerobic digestion with biogas utilization at AA Dairy, the costs associated with liquid solids separation and the revenue generated from the sale of the composted solids have been included (Moser and Mattocks, 2000 and Peranginangin and Scott, 2002). However, the results of this study indicate that anaerobic digestion prior to liquid solids separation neither enhances nor adversely impacts separation of solids. In addition, the volume of the liquid fraction is not reduced by anaerobic digestion prior to separation. Thus, the required storage capacity for the separated liquid fraction and the associated cost is not reduced. This reduces the assessment of the attractiveness of the investment in anaerobic digestion with biogas utilization at AA Dairy simply to a comparison of costs of biogas production and utilization and income derived from biogas utilization.

Capital Cost—Moser and Mattocks (2000) reported the total capital cost of the AA Dairy anaerobic digester, including the engine-generator set and electrical intertie, to be $295,700. As shown in Table 5-5, this sum includes the cost of a lift station pump including electrical work. However, this pump would be required without anaerobic digestion to transfer manure scraped from the free-stall barn alleys to the storage lagoon. It also includes the cost of the facilities required for liquid solids separation, which is not dependent on anaerobic digestion as discussed above. Therefore, the capital cost of anaerobic digestion and biogas utilization actually is $245,200 or $446 per cow as the system currently is being operated. However, the system was designed for 1,054 cows, which reduces the capital cost per cow to $233. This difference becomes highly significant because revenue from the generation of electricity will more than double if herd expansion to 1,054 cows occurs. It should be noted, however, that the engine-generator set used at AA Dairy is a used, reconditioned unit. The cost of a new unit is approximately $120,000. With a new engine-generator set the cost of the AA Dairy system would have been $300,000 or $285 per cow based on the design herd size of 1,054 cows.

<u>Value of Electricity Generated</u>—As previously discussed, AA Dairy currently generates an average of 1,429 kWh of electricity per day at the conversion efficiency of biogas energy to electrical energy of about 20 percent and an on-line efficiency of 98.8 percent. However, the conversion efficiency of 20 percent is a reflection of the less than maximum utilization of the engine-generator set capacity, which would approach 30 percent if fully utilized. Thus, AA Dairy would be able to generate one-third more electricity (2,144 kWh per day) with an engine-generator set sized for the current rate of biogas production of 42,868 ft^3 per day and 4,211 kWh per day with the engine-generator set currently in use at the system design herd size of 1,054 cows.

AA Dairy purchases electricity from the NYSEG Corporation under Service Classification No. 7 at a on-peak rate (7:00 AM to 11:30 PM) of $0.06868 per kWh and at a off-peak rate (11:30 PM to 7:00 AM) of $0.04060 per kWh with a on-peak demand charge of $11.68 per kW and a reactive charge of $0.00095 per billing reactive kilovolt-ampere hour. Based on pre-digester electricity use (i.e., prior to mid-1998) and current rates, the cost per kWh of electricity without on-site generation would range between $0.09 and $0.12 due to variation in time of use and demand charges. This range of cost per kWh reflects the increased consumption of electricity from May through October for free-stall barn ventilation for cow cooling and from September through May for increased free-stall barn lighting (Minott and Scott, 2001). For this analysis, it seems reasonable to consider $0.105 per kWh to be the fair value of the biogas-derived electricity used on site at AA Dairy.

Prior to mid-2001, AA Dairy received an average $0.025 per kWh for the electricity sold to the NYSEG Corporation. As of mid-2001, this rate was increased to $0.0525 per kWh, which is the value that will be assumed in this analysis. Because of the previously discussed problem with the engine-generator set during from January through March 2002, a continuous record of typical monthly sales of electricity to the NYSEG Corporation reflecting seasonal variation in total on-farm electricity use was not available. However, such records for 2000 and 2001 were available. During 2000 and 2001, AA Dairy respectively sold 178,970 and 191,380 kWh of electricity to the NYSEG Corporation or an average of 185,175 kWh per year. Thus, the average revenue being generated by sale of electricity at $0.0525 per kWh is estimated to be $9,722 per year.

Although electricity purchases from and sales to the NYSEG Corporation are metered, there is no metering to determine the amount of biogas-generated electricity consumed by AA Dairy. However, this value is simply the difference between the estimate biogas derived electricity generated, 521,585 kWh, and sold, 185,175 kWh, annually, which is 336,410 kWh per year. At the assumed price of $0.105 per kWh, the additional revenue generated from on-site biogas generated electricity use is estimated to be $35,323 per year. Thus, the total income produced by the AA Dairy anaerobic digester-biogas utilization system is $45,045 per year.

The current capacity for generating electricity at AA Dairy, 521,585 kWh per year, substantially exceeds the farm's estimated annual demand of 413,869 kWh per year (Minott and Scott, 2001). However, only about 64 percent of the electricity generated is consumed on site due to the inability to always satisfy demand. Yet periods when generation capacity exceeds demand also occur. Thus, an opportunity to increase revenue through load management appears to exist.

As noted earlier, AA Dairy has the potential to generate 3,315 kWh of biogas-derived electricity per day or 1,209,975 kWh per year if herd expansion to 1,054 cows occurs. Assuming on-site electrical use would double, the value of biogas-derived electricity used on site would double, increasing to $70,646 per year. The revenue generated by sale of excess electricity, 537,155 kWh per year, to the NYSEG Corporation also would increase to $28,201 per year. Thus, total income produced by the AA Dairy anaerobic digester-biogas utilization system would be $98,847 per year.

Annual Operation and Maintenance Costs—Because the AA Dairy anaerobic digester and engine-generator set have only been in operation since mid-1998, there is no long-term record on which to base an estimate of annual operating and maintenance costs. Previously, Wright and Perschke (1998) and Nelson and Lamb (2002) have estimated operation and maintenance costs for the anaerobic digestion of dairy cattle manure with biogas utilization to generate electricity to be $0.015 per kWh of electricity generated. With this approach, the operating and maintenance cost for the AA Dairy system under current operating conditions would be $7,824 per year, which is approximately three percent of the capital cost of the system. However, the operating and maintenance cost would increase to $23,055 per year or 9.4 percent of the capital cost of the system with a herd expansion to 1,054 cows. The magnitude of this increase seems unreasonable since the only significant change in operation would be an increase in the volume of manure pumped. The hours of engine-generator set operation would not change since this unit currently is being operated 24 hours per day at a partial load.

Based on the work of Moser and Langerwerf (2000), estimating annual operating and maintenance cost at five percent of the system capital cost seems like a more accurate approach. The value of five percent reported by Moser and Langerwerf was based on 16 years of operation of an anaerobic digester and engine-generator set for a herd of 400 dairy cattle and includes periodic rebuilding of the engine-generator set and renovation of the digester after 16 years of operation. For the AA Dairy system, an operating and maintenance cost rate of five percent of the system capital cost per year translates into a cost of $12,260 per year.

Economic Viability—The attractiveness of any investment generally depends on the ability of the capital investment required to generate income adequate to recover the capital invested with a rate of return on the capital invested and for management and labor that is competitive with other investment opportunities. If there is no other reason for considering anaerobic digestion, such as the need for odor control, this should be the basis for evaluating the option of adding anaerobic digestion with biogas utilization to any animal waste management system. If, however, odor control or some other benefit provided by anaerobic digestion is a necessity to continue the general farm operation, acceptance of a rate of return that is somewhat less than competitive than other investment alternatives may be acceptable if the general farm operation remains profitable.

As currently operated, the gross revenue produced by the AA Dairy anaerobic digestion-biogas utilization system from on-site use and sale of the electricity generated, as discussed above, is estimated to be $45,045 at a cost for operation and maintenance of $12,260 per year. Thus, net revenue generated is $32,785 per year. However, the AA Dairy system has the potential of producing gross revenue of $98,847 and net revenue of $86,587 per year if expansion of herd size of 1,054 cows occurs. Thus, current net revenue is adequate to recover the capital invested,

$245,200, in approximately 7.5 years if the time value of money is not considered. If the system were being operated at design capacity, the payback period would be reduced to approximately 2.8 years. At an interest rate of seven percent, these payback periods increase to approximately 11 and 4 years, respectively. Beyond these payback periods, all net revenue from biogas utilization represents net income. Assuming a system life of 20 years, the income generated by the AA Dairy system as currently operated would be approximately $295,000 or an average of $14,750 per year. With herd expansion, income would increase to approximately $1,385,250 or $69,260 per year.

If the AA Dairy system was financed over a 20-year period at the same interest rate of seven percent, the net income generated would be somewhat less, but there would be a steady stream of net income over the life of the system. Under current operating conditions, the net income would be $9,641 per year or a total of $192,820 over the life of the system. With herd expansion to the design value of 1,054 cows income would increase to $63,443 per year or a total of $1,268,860 over the life of the system.

The results of these cost analyses clearly demonstrate that anaerobic digestion of dairy cattle manure with biogas collection and utilization can provide significant environmental quality benefits as previously described while concurrently producing a significant source of income. Although the alternative of aerobic digestion can provide some of the same environmental quality benefits, no income is produced to offset capital and operating costs. Thus, total farm income is decreased rather than enhanced, as is the case with anaerobic digestion.

Under both the short-term and long-term financing scenarios described above, it appears that there would be considerable merit in replacing the current engine-generator set with unit sized for the current rate of biogas production if the plan for herd expansion is being abandoned. This system modification would increase electricity generated by 33 percent with a somewhat lower but still significant increase in net income. It probably would be most logical to make this change when the current engine-generator set requires rebuilding.

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Table 4-1. Comparison of AA Dairy manure production and characteristics with standard reference values assuming a live-weight of 1,400 lb per cow.

Parameter	**AA Dairy**	**ASAE (2001)**	**USDA (1992)**
Volume, ft^3/cow-day	2.10	1.94	1.82
Total solids, kg/cow-day	6.7	7.6	6.4
Total volatile solids, kg/cow-day	5.7	6.4	5.4
Fixed solids, kg/cow-day	1.0	1.2	1.0
Chemical oxygen demand, kg/cow-day	9.1	7.0	5.7
Total Kjeldahl nitrogen, kg/cow-day	0.28	0.29	0.29
Total phosphorus, kg/cow-day	0.048	0.060	0.044
Orthophosphate phosphorus, kg/cow-day	0.027	0.039	—
pH	7.4	7.0	—

Table 4-2. AA Dairy anaerobic digester performance summary, mg/L[*].

Parameter	Influent	Effluent	Reduction, %
Total solids	113,186^{a}±10,097	84,739^{b}±5,993	25.1
Total volatile solids	96,080^{a}±9,477	67,518^{b}±4,446	29.7
Fixed solids	17,106^{a}±1,495	17,221^{a}±2,461	—
Chemical oxygen demand	153,496^{a}±77,178	89,144^{b}±23,185	41.9
Soluble chemical oxygen demand	24,239^{a}±6,568	16,961^{b}±7,073	30.0
Total volatile acids	3,687 ^{a} ±806	513 ^{b}±227	86.1
Total Kjeldahl nitrogen	4,631^{a}±513	5,111^{a}±894	—
Organic nitrogen	2,500^{a}±491	2,268^{a}±891	—
Ammonia nitrogen	2,159^{a}±387	2,881^{b}±322	+33.4[†]
Total phosphorus	813^{a}±124	838^{a}±124	—
Orthophosphate phosphorus	457^{a}±104	562^{b}±90	+23.0[†]
pH	7.4^{a}±0.3	7.9^{b}±0.1	—

[*] Means in a row with a common superscript are not significantly different ($P<0.01$).

[†] Increase in concentration.

Table 4-3. AA Dairy anaerobic digester reductions of total solids, total volatile solids, chemical oxygen demand, and soluble chemical oxygen demand.

Parameter	Reduction, lb/day
Total solids	2,052
Total volatile solids	2,060
Chemical oxygen demand	4,641
Soluble chemical oxygen demand	525

Table 4-4. Comparison of AA Dairy anaerobic digester $\log_{10}$ influent and effluent densities of fecal coliform bacteria and *M. avium paratuberculosis*.

	Influent	Effluent	Reduction
Fecal coliforms			
CFU/g*	6.08±0.59	3.30±0.73	2.78
M. avium paratuberculosis			
CFU/g	3.94±0.72	1.86±0.72	2.08

*Log_{10} colony-forming units per g of manure

Table 4-5. AA Dairy Biogas Composition.

Parameter	% by volume
Methane	59.1
Carbon dioxide	39.2
Hydrogen sulfide	0.193
Ammonia	0.0015
Other gases	1.5055

Table 4-6. Methane and total biogas production as functions of chemical oxygen demand and total volatile solids destruction.

Parameter	Biogas	Methane
$ft^3/lb\ COD_D$	9.24	5.46
$ft^3/lb\ TVS_D$	20.81	12.30

Table 4-7. Comparison of the characteristics of the AA Dairy anaerobic digester effluent (separator influent) with the separated liquid and solid fractions, mg/L[*].

Parameter	Digester effluent	Separated liquid	Separated solids
Total solids	84,739^{a}±5,993	51,088^{b}±1,357	247,444^{c}±18,153
Total volatile solids	67,518^{a}±4,446	35,763^{b}±1,280	220,982^{c}±18,235
Fixed solids	17,221^{a}±2,461	15,325^{b}±988	26,463^{c}±2,906
Chemical oxygen demand	89,144^{a}±23,185	54,744^{b}±6,068	224,040^{c}±78,277
Soluble chemical oxygen demand	16,961^{a}±7,073	15,185^{a}±4,474	16,350^{a}±5,160
Total Kjeldahl nitrogen	5,111^{a}±894	4,723^{a}±601	5,374^{a}±1,076
Ammonia nitrogen	2,881^{a}±322	2,964^{a}±305	2,656^{a}±502
Organic nitrogen	2,268^{a}±891	1,837^{ab}±570	2,625^{ac}±755
Total phosphorus	838^{a}±124	802^{a}±90	1,106^{b}±308
Orthophosphate phosphorus	526^{a}±90	538^{a}±96	620^{a}±156
pH	7.9^{a}±0.1	7.9^{a}±0.2	8.5^{b}±0.2

[*] Means in a row with a common superscript are not significantly different (P<0.01).

Table 4-8. Comparison of AA Dairy $\log_{10}$ densities of fecal coliform bacteria and *M. avium paratuberculosis* in the anaerobic digester effluent with separated liquid and solid fraction densities[•].

	Digester effluent	Separated liquid	Separated solids
Fecal coliforms			
CFU/g[†]	$3.30^{a} \pm 0.73$	$2.66^{ab} \pm 0.88$	$2.55^{b} \pm 0.88$
M. avium paratuberculosis			
CFU/g	$1.94^{a} \pm 0.62$	$1.26^{ab} \pm 0.95$	$0.56^{b} \pm 0.88$

[*] Means in a row with a common superscript are not significantly different ($P<0.01$).

[†] Log_{10} colony-forming units per g of manure.

Table 4-9. Distributions of constituents of AA Dairy anaerobic digester effluent following separation.

Parameter	Liquid fraction, %	Solid fraction, %
Total solids	83	17
Total volatile solids	83	17
Fixed solids	93	7
Chemical oxygen demand	85	15
Total Kjeldahl nitrogen	95	5
Ammonia nitrogen	96	4
Organic nitrogen	94	6
Total phosphorus	95	5
Orthophosphate phosphorus	96	4

Table 4-10. Comparison of the characteristics of the AA Dairy storage pond influent with the pond contents.

Parameter	Storage pond influent	Storage pond influent (adjusted for dilution)	Storage pond
Total solids, mg/L	51,088±1,357	29,239	28,407±2,892
Total volatile solids, mg/L	35,763±1,280	20,468	18,634±2,268
Fixed solids, mg/L	17,221±2,461	9,856	9,774±794
Chemical oxygen demand, mg/L	54,744±6,068	31,331	31,399±1,396
Soluble chemical oxygen demand, mg/L	15,185±4,474	8,691	12,233±2,837
Total Kjeldahl nitrogen, mg/L	4,723±601	2,702	2,564±126
Ammonia nitrogen, mg/L	2,964±305	1,696	1,553±690
Organic nitrogen, mg/L	1,837±570	1,051	1,012±566
Total phosphorus, mg/L	802±90	459	459±42
Orthophosphate phosphorus, mg/L	538±96	308	356±47

Table 4-10. Continued.

pH	7.9±0.2	—	7.6±01
Fecal coliforms, CFU/g[*]	2.66±0.88	1.52	2.75±0.36
M. avium paratuberculosis, CFU/g	1.26±0.95	—	No data

[*] Log$_{10}$ colony-forming units per g of manure.

Table 4-11. Comparison of Patterson Farms manure production and characteristics with standard reference values assuming a live-weight of 1,400 lb per cow.

Parameter	Patterson Farms	ASAE (2001)	USDA (1992)
Volume, ft^3/cow-day	2.35	1.94	1.82
Total solids, kg/cow-day	7.1	7.6	6.4
Total volatile solids, kg/cow-day	5.8	6.4	5.4
Fixed solids, kg/cow-day	1.3	1.2	1.0
Chemical oxygen demand, kg/cow-day	9.4	7.0	5.7
Total Kjeldahl nitrogen, kg/cow-day	0.28	0.29	0.29
Total phosphorus, kg/cow-day	0.045	0.060	0.044
Orthophosphate phosphorus, kg/cow-day	0.020	0.039	—
pH	7.4	7.0	—

Table 4-12. Comparison of the characteristics of Patterson Farms separator influent with the separated liquid and solid fractions, mg/L[*].

Parameter	Separator influent	Separated liquid	Separated solids
Total solids	107,063^{a}±5,972	79,463^{b}±8,961	248,600^{c}±11,716
Total volatile solids	87,490^{a}±5,333	61,389^{b}±7,374	227,622^{c}±11,071
Fixed solids	19,572^{ab}±1,564	18,074^{a}±1,697	20,978^{b}±2,401
Chemical oxygen demand	141,871^{a}±21,057	96,513^{b}±24,649	280,842^{c}±65,196
Soluble chemical oxygen demand	22,668^{a}±9,821	22,290^{a}±5,057	18,701^{b}±6,926
Total Kjeldahl nitrogen	4,237^{a}±609	4,015^{a}±522	3,942^{a}±785
Ammonia nitrogen	1,999^{a}±310	1,938^{a}±297	1,496^{b}±301
Organic nitrogen	2,239^{a}±597	2,078^{a}±409	2,444^{a}±594
Total phosphorus	677^{a}±109	608^{a}±96	510^{b}±129
Orthophosphate phosphorus	306^{a}±98	280^{a}±84	214^{a}±107
pH	7.5^{a}±0.2	7.5^{a}±0.2	8.2^{b}±0.2

[*] Means in a row with a common superscript are not significantly different ($P<0.01$).

Table 4-13. Comparison of Patterson Farms $\log_{10}$ densities of fecal coliform bacteria and *M. avium paratuberculosis* in the anaerobic digester effluent with separated liquid and solid fraction densities*.

	Separator influent	Separated liquid	Separated solids
Fecal coliforms			
CFU/g[†]	$5.68^a \pm 0.47$	$5.86^a \pm 0.53$	$5.28^a \pm 0.64$
M. avium paratuberculosis			
CFU/g	$4.00^a \pm 0.48$	$3.05^b \pm 0.50$	$2.71^b \pm 1.13$

[*] Means in a row with a common superscript are not significantly different ($P<0.01$).

[†] Log_{10} colony-forming units per g of manure.

Table 4-14. Distributions of constituents of Patterson Farms separator influent following separation.

Parameter	Liquid fraction, %	Solid fraction, %
Total solids	84	16
Total volatile solids	84	16
Fixed solids	48	52
Chemical oxygen demand	85	15
Total Kjeldahl nitrogen	94	6
Ammonia nitrogen	96	4
Organic nitrogen	93	7
Total phosphorus	96	4
Orthophosphate phosphorus	97	3

Table 4-15. Comparison of the characteristics of the AA Dairy storage pond influent with the pond contents.

Parameter	Storage pond influent	Storage pond influent (adjusted for dilution)	Storage pond
Total solids, mg/L	79,463±8,961	71,752	71,630±7,250
Total volatile solids, mg/L	61,389±7,374	55,432	54,493±4,992
Fixed solids, mg/L	18,074±1,697	16,320	17,134±2,265
Chemical oxygen demand, mg/L	96,513±24,649	87,147	84,819±7,291
Soluble chemical oxygen demand, mg/L	22,290±5,057	20,127	20,032±4,078
Total Kjeldahl nitrogen, mg/L	4,015±522	3,625	3,315±504
Ammonia nitrogen, mg/L	1,938±297	1,750	1,531±798
Organic nitrogen, mg/L	2,078±409	1,875	1,784±301
Total phosphorus, mg/L	608±96	549	549±53
Orthophosphate phosphorus, mg/L	280±84	252	301±51

Table 4-15. Continued.

pH	7.5±0.2	—	7.2±0.2
Fecal coliforms, CFU/g[*]	5.86±0.53	5.29	4.63±0.25
M. avium paratuberculosis, CFU/g	3.05±0.50	2.75	2.85±0.06

[*] Log$_{10}$ colony-forming units per g of manure.

Table 5-1. Comparison of AA Dairy and Patterson Farms rates of production of manure and its various constituents.

	AA Dairy	Patterson Farms
Volume, ft^3/cow-day	2.10	2.35
Total solids, kg/cow-day	6.7	7.1
Total volatile solids, kg/cow-day	5.7	5.8
Fixed solids, kg/cow-day	1.0	1.3
Chemical oxygen demand, kg/cow-day	9.1	9.4
Total Kjeldahl nitrogen, kg/cow-day	0.28	0.28
Total phosphorus, kg/cow-day	0.048	0.045
Orthophosphate phosphorus, kg/cow-day	0.027	0.020
pH	7.4	7.4

Table 5-2. Comparison of AA Dairy anaerobic digester and Patterson Farms separator influent characteristics, mg/L.

Parameter	AA Dairy	Patterson Farms
Total solids	113,186±10,097	107,063±5,972
Total volatile solids	96,080±9,477	87,490±5,333
Fixed solids	17,106±1,495	19,572±1,564
Chemical oxygen demand	153,496±77,178	141,871±21,057
Soluble chemical oxygen demand	24,239±6,568	22,668±9,871
Total Kjeldahl nitrogen	4,631±513	4,237±609
Ammonia nitrogen	2,159±387	1,999±310
Organic nitrogen	2,500±491	2,239±597
Total phosphorus	813±124	677±109
Orthophosphate phosphorus	457±104	306±98
pH	7.4±0.3	7.5±0.2

Table 5-3. Comparison of the characteristics of the AA Dairy and Patterson Farms separated solids, mg/L.

Parameter	AA Dairy	Patterson Farms
Total solids, mg/L	247,444±18,153	248,600±11,716
Total volatile solids, mg/L	220,982±18,235	227,622±11,071
Fixed solids, mg/L	26,463±2,906	20,978±2,401
Chemical oxygen demand, mg/L	224,040±78,277	280,842±65,196
Soluble chemical oxygen demand, mg/L	16,350±5,160	18,701±6,926
Total Kjeldahl nitrogen, mg/L	5,374±1,076	3,942±785
Ammonia nitrogen, mg/L	2,656±502	1,496±301
Organic nitrogen, mg/L	2,625±755	2,444±594
Total phosphorus, mg/L	1,106±308	510±129
Orthophosphate phosphorus, mg/L	620±156	214±107
pH	8.5±0.2	8.2±0.2
Fecal coliforms, CFU/g*	2.55±0.88	5.28±0.64
M. avium paratuberculosis, CFU/g	0.56±0.88	2.71±1.13

*Log_{10} colony-forming units per g of manure.

Table 5-4. Comparison of the characteristics of the AA Dairy and Patterson Farms separated liquid, mg/L.

Parameter	AA Dairy	Patterson Farms
Total solids, mg/L	51,088±1,357	79,463±8,961
Total volatile solids, mg/L	35,763±1,280	61,389±7,374
Fixed solids, mg/L	15,325±988	18,074±1,697
Chemical oxygen demand, mg/L	54,744±6,068	96,513±24,649
Soluble chemical oxygen demand, mg/L	15,185±4,474	22,290±5,057
Total Kjeldahl nitrogen, mg/L	4,723±601	4,015±522
Ammonia nitrogen, mg/L	2,964±305	1,938±297
Organic nitrogen, mg/L	1,837±570	2,078±409
Total phosphorus, mg/L	802±90	608±96
Orthophosphate phosphorus, mg/L	538±96	280±84
pH	7.9±0.2	7.5±0.2
Fecal coliforms, CFU/g*	2.66±0.88	5.86±0.53
M. avium paratuberculosis, CFU/g	1.26±0.95	3.05±0.50

*Log_{10} colony-forming units per g of manure.

Table 5-5. Cost of the AA Dairy anaerobic digestion with biogas utilization and liquid solids separation system (Moser and Mattocks, 2000).

Item	Cost
Lift station/Mix tank*	$12,500
Digester	$121,000
Engine-generator set†	$32,000
Electrical and intertie	$33,200
Structure for engine-generator set, piping, etc.	30,500
Liquid solids separation	$38,000
Engineering	$24,000
Start-up	$4,500
Total	$295,700

*Only pump and electrical work.

†Used, reconditioned unit.