FINAL

AN EVALUATION OF A MESOPHILIC, MODIFIED PLUG FLOW ANAEROBIC DIGESTER FOR DAIRY CATTLE MANURE

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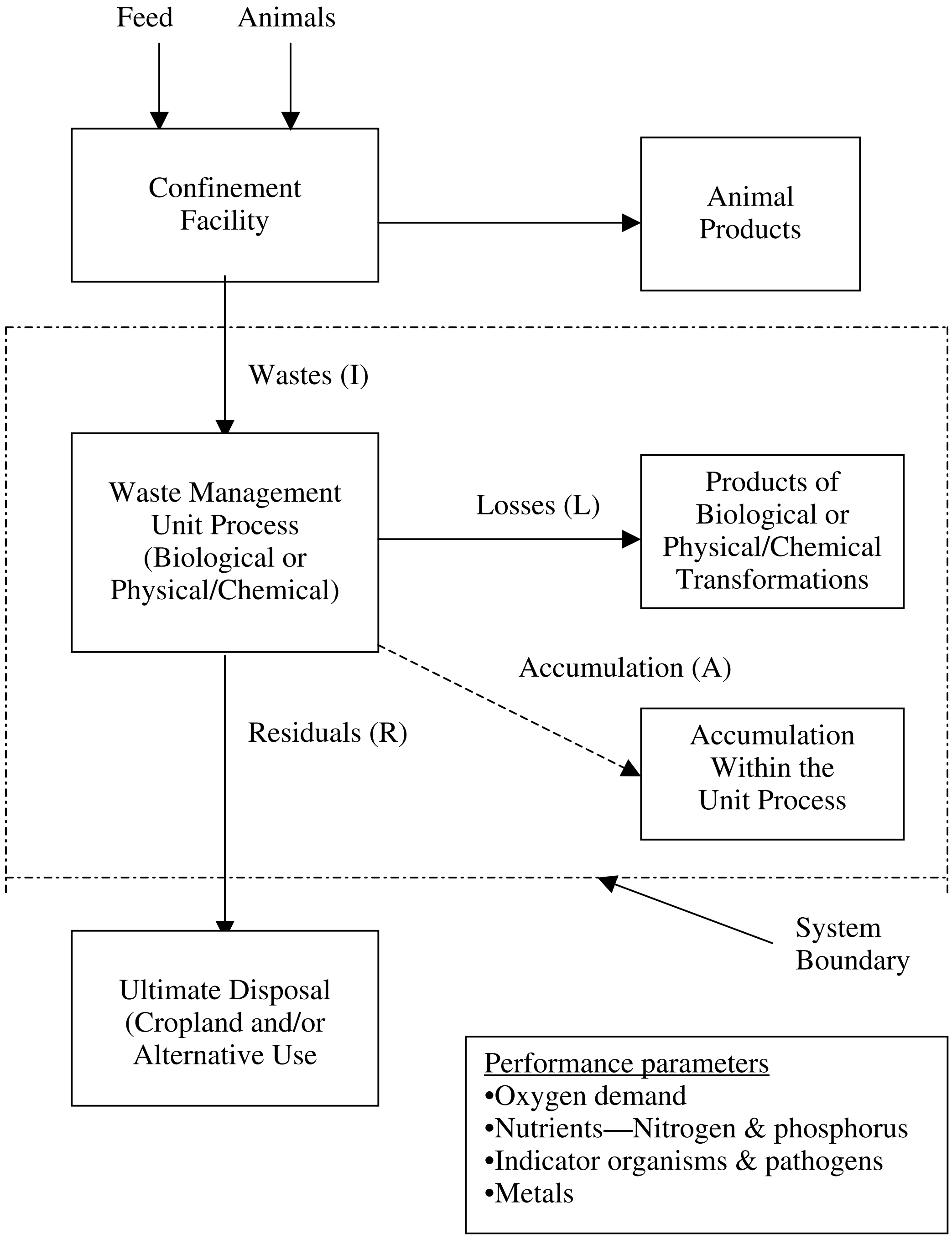
TABLES

PREFACE

This report summarizes the results from one of a series of AgSTAR studies designed to more fully characterize: 1) the air and water quality improvements provided by anaerobic digesters for managing manure and other wastes in the swine and dairy industries, and 2) the associated costs. The 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, engineers, and the regulatory community can better identify specific 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.

ACKNOWLEDGEMENTS

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SECTION 1

SUMMARY AND CONCLUSIONS

The objective of this study was to characterize the performance under commercial conditions of: 1) a modified form of a full-scale, plug-flow anaerobic digester for dairy cattle manure in a cold climate, and 2) a screw press type separator for recovery of coarse solids from the digester effluent. The performance of this waste management system was characterized based on the: 1) reductions in potential air and water quality impacts, 2) net energy recovered from the biogas produced, and 3) differential between capital and operating costs and the income realized from the biogas and separated solids produced.

The site of this 12-month study was Gordondale Farms, a 3,200-acre dairy farm located in Nelsonville, Wisconsin. At the beginning of this study in January 2004, the average size of the Gordondale Farms milking herd was 750 Holstein-Friesian cows. On 15 July, the average milking herd size was increased to 860 cows and then remained constant through the end of the study in December 2004. The milking herd is housed in a naturally ventilated free-stall barn, which is connected to a milking center.

Gordondale Farms uses a modified form of a plug-flow anaerobic digester with vertical gas mixing. The biogas produced is delivered to an on-site engine-generator set owned and operated by Alliant Energy, the local electric utility. Gordondale Farms is paid for the biogas delivered at the rate of $0.015 per kilowatt-hour generated and delivered to Alliant's transmission system. The anaerobic digester, which has been in operation since March 2002, was designed and constructed by GHD, Inc. of Chilton, Wisconsin.

After digestion, the coarse solids in the digester effluent are removed mechanically using a FAN screw press separator. The remaining liquid is discharged to a holding tank for short-term storage before land application to cropland. The separated solids are stacked for partial drying and then are either used on-site or sold as bedding.

The results of this study confirm-the environmental quality benefits realized by the anaerobic digestion of dairy cattle manure with biogas collection for the generation of electricity. These results also confirm that the economic value of the electricity generated and the stabilized solids recovered can be adequate to recover the capital investment in a reasonable period and then generate a long-term income stream. The findings of the study are summarized in Table 1-1 and discussed below.

Table 1-1. Summary of observed impacts of anaerobic digestion on semisolid dairy cattle manure management at Gordondale Farms.

Parameter	**Impact**
Odor	Substantial reduction
Greenhouse gas emissions	Methane—substantial reduction (2.32 tons per cow-yr on a carbon dioxide equivalent basis) Carbon dioxide—1.33 tons per cow-yr associated with the reduction in fossil fuel use to generate electricity
Ammonia emissions	No significant reduction
Potential water quality impacts	Oxygen demand—substantial reduction (5.1 lb per cow-day) Indicator organisms and potentially pathogens—significant reduction (Fecal coliforms: >99%) (Fecal streptococcus: >90%) Nutrient enrichment—no reduction
Economic impact	Significant increase in net farm income ($101 per cow-year after recovery of capital invested in 6.3 years)

Odors

The most readily apparent benefit of the use of anaerobic digestion at Gordondale Farms is the low level of the noxious odors commonly associated with dairy cattle manure management systems. 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 39.6, 38.5, and 87.8 percent, respectively. With these reductions, additional degradation during storage under uncontrolled anaerobic conditions and the associated odors are minimized.

Greenhouse Gas Emissions

Perhaps the most significant air quality impact is the reduction of methane emissions. Methane is a greenhouse gas with 21 times the heat-trapping capacity of carbon dioxide. The reduction in methane emissions, on a carbon dioxide equivalent basis, was determined to be 3.03 tons per cow-year (2,610 tons per year for the current 860-cow Gordondale farms milking herd). In addition, the electricity generated using biogas has the potential of reducing carbon dioxide emissions by displacing fossil fuel combustion that otherwise would have been used to generate the electricity. Under current operating conditions, this emission reduction is estimated to be 1,077 tons per year, which translates into 1.33 tons per cow-year. Given the absence of oxidized forms of nitrogen in dairy cattle manure and the requirement of anaerobic conditions for methane production, the potential for nitrous oxide emissions is nil.

Other Gaseous Emissions

Analysis of the biogas produced at Gordondale Farms indicated the presence of only a nominal concentration, 0.000347 percent by volume, of ammonia (Table 4-5). The results of this analysis in combination with the total Kjeldahl nitrogen balance results (Table 4-2) indicate that 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 Gordondale Farms biogas, 0.310 percent by volume, indicates that emissions of oxides of sulfur during biogas combustion potentially could be significant. However, the increase in pH occurring digestion (Table 4-2) should reduce the potential for emissions of hydrogen sulfide and the associated noxious odor from the digester effluent during storage and land application.

Water Quality Impacts

<u>Oxygen Demand</u>—The study results show (Table 4-2) that anaerobic digestion can substantially reduce dairy cattle manure total volatile solids (39.5 percent) and chemical oxygen demand (38.5 percent). 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.

<u>Pathogens</u>—As shown in Table 4-4, mesophilic anaerobic digestion at an average hydraulic retention time of 29 days reduced the mean densities of the fecal coliform group of enteric bacteria by 99 percent and fecal streptococcus group by 90 percent. These groups of bacteria serve as indicators of pathogen destruction potential and suggest that anaerobic digestion also can achieve significant reductions in the densities of any pathogens present, such as *Mycobacterium avium paratuberculosis. M. avium paratuberculosis* is responsible for chronic enteritis (paratuberculosis or Johne's disease) in cattle and

other ruminants and is suspected to be the causative agent in Crohn's disease in humans. 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.

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. However, results of this study indicate that separation of coarse solids after anaerobic digestion-reduces the mass of nitrogen and phosphorus in the remaining liquid fraction by about 18 and 38 percent, respectively (Table 4-8).

Economic Impact

The results of this study also confirm that the modified plug flow anaerobic digester with biogas utilization is an economically attractive approach. The system can produce revenue adequate to recover the capital investment and increase farm net income through the revenue derived from electricity generated and the coarse solids recovered from the digester effluent. Under the current contractual agreement with Alliant Energy, it is estimated that Gordondale Farms will recover their capital investment without interest in 6.3 years and then have an increase annual net farm income of $101 per cow. If Gordondale Farms had purchased the engine-generator set (Alliant Energy currently owns and operates the engine-generator set), their capital investment would have increased from $550,000 to $748,000, but only six years would have been required to recover their capital investment due to the additional revenue from electricity generated. In addition, the annual net farm income after capital recovery would have increased to $144 per cow. 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. This study also showed, however, that income from this system could be increased beyond that currently recognized by Gordondale Farms. Improving-the efficiency of the conversion of biogas to electricity would increase electricity generation and the associated income. It should be noted, however, that the economic attractiveness of anaerobic digestion with biogas utilization at Gordondale Farms is due, at least partially, to the relatively high fraction of total volatile solids (47 percent) that are readily biodegradable.

SECTION 2

INTRODUCTION

Anaerobic digestion is a controlled biological process that can substantially reduce the air and water quality impacts of livestock and poultry manures that are managed as a liquid or slurry. Unlike comparable aerobic waste stabilization processes, energy requirements are minimal. A relatively small fraction of the biogas energy produced is required to operate an anaerobic digestion system. The remaining biogas energy is available for use as a boiler fuel or to generate electricity. Thus, anaerobic digestion with biogas utilization produces a source of revenue to offset some or all process costs and possibly 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, due to technical problems and as supplies of conventional fuels increased and prices declined. A substantial majority of the anaerobic digesters constructed at livestock and poultry operations in the 1970s failed for a variety of reasons. However, the experience gained during this period led to refined 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. Four primary factors contributed to this renewal of interest. One was the need for a cost-effective strategy for reducing manure-related odors from storage facilities, including anaerobic lagoons and land application sites. Another was the re-emerging concern about the impacts of livestock and poultry manures on water quality. The third was recognition that many of the technical problems encountered in the 1970s had been resolved. 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 and water quality impacts of livestock and poultry manures (Martin and Loehr, 1976 and Martin *et al*., 1981), the cost was 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 increased greenhouse gas emissions associated with the generation of the electricity required.

Objective

The objective of this study was to characterize the performance under commercial conditions of: 1) a modified form of a full-scale, plug-flow anaerobic digester described below for dairy cattle manure in a cold climate and 2) a screw press type separator for recovery of coarse solids from the digester effluent. Characterization of the performance of this waste management system was based on the: 1) reductions in potential air and water quality impacts, 2) net energy recovered from the biogas produced, and 3) differential between capital and operating costs and income realized from the biogas and separated solids produced.

SECTION 3

METHODS AND MATERIALS

Study Site

The site of this study was Gordondale Farms, a 3,200-acre dairy farm located in Nelsonville, Wisconsin. Nelsonville is in Portage County near Stevens Point in central Wisconsin. At the beginning of this 12-month study in January 2004, the average size of the Gordondale Farms' milking herd was 750 Holstein-Friesian cows. On 15 July, the average milking herd size was increased to 860 cows and then remained constant through the end of the study. Milk production is estimated to average 21,000 lb per cow-yr. The milking herd is housed in a naturally ventilated free-stall barn, which is connected to a milking center.

Manure is removed from the free-stall barn alleys daily by scraping with a skid-steer loader to a sump. From this sump, the accumulated manure flows by a combination of gravity and fluming with milking center wastewater to an influent holding tank containing a chopper type pump. The chopper-pump mixes the influent in the holding tank and transfers the manure into the anaerobic digester. After digestion, the coarse solids in the digester effluent are removed mechanically using a FAN screw press separator. The remaining liquid is discharged to a holding tank for short-term storage before land application to cropland.

The separated solids are stacked for partial drying before use as bedding. An estimated 55 tons of separated solids are used for bedding each week. The excess solids, approximately 22 tons per week, are sold to another dairy farm at $15 per ton for use as bedding. Gordondale Farms estimates that the on-site use of separated solids for bedding results in a $60,000 per year increase in gross farm income due to the avoided cost for bedding, and the sale of excess separated solids adds an additional $8,580 per year.

The anaerobic digester, which has been in operation since March 2002, was designed and constructed by GHD, Inc. of Chilton, Wisconsin for a milking herd of 750 cows. The digester dimensions are 91 ft long by 62.3 ft wide with an operating depth of 12.5 ft. The estimated operating volume is 70,866 ft^3. The design hydraulic retention time (HRT) for the digester based on the assumption of a 750 cow milking herd was 22 days with a predicted electricity generation potential of 3.7 kW per cow-day or 2,775 kWh per day.

The digester is described by the designer, GHD, Inc., as a two-stage modified plug-flow mesophilic digester with vertical gas mixing. Unlike a conventional plug-flow digester, the influent channel is separated into two compartments to allow, at least theoretically, acidogenesis to occur separately from methane formation. Hence, the use by the designer of the term two-stage to describe the digester. However, the relatively high density of methanogens in dairy cattle manure makes the separation of acidogenesis and methanogenesis unlikely. In addition, the Gordondale Farms' digester has two parallel channels connected at one end resulting in a U-shaped flow pattern. Thus, influent enters and effluent exits at the same end of the digester at adjacent locations. This configuration is not common but is being used where space or desirability of locating influent and effluent in adjacent locations are more effective for the project.

The Gordondale Farms' anaerobic digester is a poured in-place, reinforced concrete tank covered and sealed with reinforced concrete panels. The digester is partially below grade and is insulated to enable maintenance of mesophilic conditions during cold weather. It has been in continuous operation since March 2002.

Captured biogas is used to fuel a 150 kW engine-generator set. The engine, a Caterpillar 3406 is a diesel engine modified by the addition of spark ignition system to use low pressure/low energy biogas as a fuel. The unit is rated at 140 kW when fueled with biogas. The generator is an induction type unit with the following specifications: three phase, 480 volts, and 312 amps at 1,835 rpm. The engine-generator set is owned and operated by Alliant Energy Corporation, Madison, Wisconsin and all electricity generated is delivered directly to the Alliant transmission system. Alliant energy pays Gordondale Farms at the rate of \$0.015 per kWh delivered and all electricity used by Gordondale Farms is purchased from Alliant Energy at retail rates. Waste heat from the engine-generator set cooling and exhaust system is recovered and used at no cost by Gordondale Farms for digester and milking center space and water heating. Biogas produced during periods when the engine-generator set is out of service for maintenance and repairs is flared to prevent an excessive increase in digester biogas pressure.

Data Collection

The performance of the anaerobic digester and liquid-solids separation unit was characterized using materials balances. The material balances were developed based on measured concentrations of selected parameters in the digester influent and effluent and the liquid and solid phase effluents from the liquid-solids separation unit and mass flow estimates. Grab samples from each waste stream were collected semi-monthly for analysis from January through December 2004. Each sample collected 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.

The influent flow rates for the digester and the liquid-solids separation unit were estimated by recording the time of chopper pump operation. The chopper pump transfers manure from an influent holding tank into the Gordondale digester. A float switch controls this pump, which transfers a constant volume of manure into the digester during each operating cycle. Based on the dimensions of the influent holding tank, it was determined that the average flow rate for this pump is approximately 521 gallons per minute. 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.

During each sampling episode, data also were collected for volume of biogas utilized, biogas methane and carbon dioxide content, electricity generation, and hours of engine-generator set and digester influent pump operation between sample collection events. In addition, measurements were recorded of cooling and exhaust system waste heat-used for digester and milking center space and water heating.

Sample Analyses

Physical and Chemical Parameters—All digester influent and effluent samples collected were analyzed on an "as received" basis 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), soluble orthophosphate phosphorus (SPO_4-P), and pH. Each FAN screw press separator liquid and solid phase effluent sample was analyzed to determine concentrations of TS, TVS, TKN, NH_4-N, and TP also on an "as received" basis.

U.S. Environmental Protection Agency (1983) methods were used for TS, TVS, TKN, TP, SPO_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 Northern Lake Service, Inc. of Crandon, Wisconsin, an analytical laboratory certified by the Wisconsin Department of Natural Resources for water and waste analysis.

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 Gordondale Farms. The study was a laboratory scale study in which two liters of 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 concentration on days 0, 15, 20, 30, 45, and 55.

Microbial Parameters—Two microbial parameters were used to characterize the potential fate of pathogenic microorganisms in the Gordondale Farms waste management system. One parameter was the fecal coliform group of bacteria (fecal coliforms), a group of bacteria that includes *Escherichia coli*, *Klebsiella pneumoniae*, and other species that-are common inhabitants of the gastro-intestinal tract of all warm-blooded animals. The second parameter was the fecal streptococcus (fecal strep) group of bacteria, a group of bacteria that includes *S. faecalis*, *S. faecium*, and other species that also are common inhabitants of the gastro-intestinal tract of all warm-blooded animals. The presence of fecal coliforms and fecal streptococci are a commonly used indicator of fecal contamination and the possible presence of pathogenic microorganisms. In addition, a reduction in fecal coliform and fecal streptococci densities serves as an indicator of reductions in the densities of pathogenic microorganisms that also may be present. Densities of both groups of indicator organisms were estimated using the multiple tube fermentation technique (American Public Health Association, 1995) also by Northern Lakes Service, Inc.

Biogas Composition—On the days that digester and screw press separator influent and effluent samples were collected for analysis, biogas samples also were collected for determination of methane and carbon dioxide content using a CES-Landtec Gem™ 500 Landfill Gas Monitor. These determinations were performed at the Hickory Meadows Landfill in Hilbert, Wisconsin. In addition, a random sample of the Gordondale Farms' biogas was analyzed by Badger Laboratories and Engineering, Inc., Neehah, Wisconsin to determine concentrations of hydrogen sulfide (H_2S) and ammonia (NH_3). The determination of the H_2S content was performed using ASTM Method D-5504 (ASTM International, 1990). The same sample was analyzed to determine NH_3 content using EPA Method 350.1.

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 pair-wise comparisons of means (Steel and Torrie, 1980) was used. To equalize variances, densities of fecal coliform and fecal streptococcus bacteria transformed logarithmically before calculation of means and standard deviations and comparisons of means to determine the statistical significance of differences.

The refractory fraction of TVS in the as excreted manure was estimated using the results of the batch biodegradability study. The estimate was 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 theoretically should be linear with the ordinate axis intercept representing the refractory fraction of TVS.

SECTION 4

RESULTS

Manure Production and Characteristics

As shown in Table 4-1, the volume of manure generated per cow-day at Gordondale Farms based on the volume of influent entering the digester, is significantly higher than the standard reference value published by USDA (1992). However, the influent to this digester includes milking center wastewater, which is used to flume the manure scraped from the free-stall barn into the digester influent holding tank. The USDA estimate does not include any water used for cleaning or accidental spillage from drinkers. If it is assumed that the USDA estimate of manure production is valid for Gordondale Farms, it appears that the rate of process water generation (milking center wastewater, spillage from drinkers, and other water used for cleaning) on this farm is about 1.22 ft^3 (9.1 gal) per cow-day, which is a reasonable value.

While the excretion rates for TS, TVS, and FS for Gordondale Farms also are somewhat higher than USDA (1992) values, it appears that the liberal use of separated solids for bedding in combination with unpaved free-stalls may be responsible, at least partially, for these differentials. The FS content of these separated solids, 31 percent, is approximately double the USDA value of-15.6 percent for typical dairy cattle manure. The separated solids used for bedding also may be a factor contributing to the significantly higher total phosphorus excretion rates although feeding practices usually are the primary factor.

Digester Operating Conditions

As noted earlier, the Gordondale Farms herd size increased from 750 to 860 cows on 15 July 2004. Before this increase, the average digester influent flow rate was 23.0±1.3 gal per cow-day, which translates into an HRT of 30.8±1.8 days. After the herd size increased, the average digester influent flow rate decreased slightly to 22.2±1.0 gal per cow-day. This decreased flow rate moderated the reduction in HRT due to the addition of 110 cows to 27.9±1.2 days. Presumably, this reduction in influent flow rate per cow-day was due to a reduction in water use per cow in the milking center. Because the difference in HRT between these two periods was not found to be statistically significant ($P<0.01$), the 12-month average influent flow rate of 29.1±2.1 gal per cow-day was used. This flow rate translates into an average HRT of 29.1±2.1 days. This HRT is seven days longer than the original design value for this digester (an HRT of 22 days).

Waste Stabilization

Table 4-2 summarizes the performance of the Gordondale Farms' plug-flow anaerobic digester by comparing mean influent and effluent concentrations. The results show substantial and statistically significant ($P<0.01$) reductions in TS, TVS, COD, SCOD, and TVA concentrations, as would be expected. In addition as expected was the statistically significant decease in the concentration of ON and concurrent increase in NH_4-N concentration, which reflects the mineralization of ON during digestion. The absence of statistically significant differences in influent and effluent TKN and TP concentrations suggest that this digester is operating in an ideal plug flow mode with no settling and accumulation of solids occurring. However, the statistically significant difference between influent and effluent FS concentrations contradicts this conclusion. While the reason for the difference between influent and effluent FS concentrations is unclear, it may be that the first compartment in the influent channel is functioning as a grit chamber and trapping FS, such as soil particles from the unpaved free-stalls. However, GHD, Inc. has indicated that no accumulation of settled solids in this chamber has been detected by periodic probing. The absence of a statistically significant difference between influent and effluent TKN concentrations suggests that any NH_3 desorption during the mesophilic anaerobic digestion of dairy cattle manure is, at most, nominal.

The differences between influent and effluent concentrations of TS, TVS, COD, and SCOD (Table 4-2) translate into the mass reductions presented in Table 4-3. The difference between the mass reductions of TS and TVS is a reflection of the difference between influent and effluent FS concentrations.

Biodegradability

The results of the batch biodegradability study indicate that 47 percent of the TVS are readily biodegradable and 53 percent are refractory. This suggests, in an engineering context, that 84 percent of the biogas production potential of the Gordondale Farms dairy manure is being realized at an HRT of approximately 29 days.

Indicator Organism and Pathogen Reduction

As shown in Table 4-4, the $\log_{10}$ densities of both the fecal coliform and fecal streptococcus groups of bacteria were reduced substantially in the Gordondale Farms' anaerobic digester. On a colony-forming unit (CFU) per 100 ml of manure basis, the reduction in the density of fecal coliforms was over 99 percent while the reduction in fecal streptococcus density was somewhat greater than 90 percent.

Biogas Production and Characteristics

Production—The biogas produced at Gordondale Farms is used by Alliant Energy to generate electricity and the waste heat from the engine-generator set is used for digester and milking center water and space heating. When the engine-generator set is out of service, biogas is flared. Only the biogas utilized to fuel the engine-generator set is metered.

At the beginning of this studying January 2004, a Roots gas meter was reinstalled after removal in the previous year due to the mistaken belief that it was restricting gas flow to the engine-generator set and the amount of electricity generated. However, Gordondale Farms removed the meter again in mid-February for the same reason. Due to funding considerations, it was not possible to install a new, non-flow restricting type gas meter, a FCI FlexMASSter thermal mass flow meter, until August 2004. When this new meter was installed, it was established that the Roots gas meter was not restricting biogas flow or electrical output.

Biogas production was estimated to be 93,501 ft^3 per day. Because of the circumstances described above, biogas production before July (when the herd size was increased to 860 cows) was determined based on gas meter readings during two January and one February sampling episodes. During this period, biogas production averaged 99,762±7,826 ft^3 per day, which translates into 133±10.4 ft^3 per cow-day. After the herd size was increased, biogas production decreased slightly to an average of 93,501±4,011 ft^3 per day or 109±5 ft^3 per cow-day. The reason for the reduction in biogas production is unclear given the nominal reduction in HRT that occurred when the herd size increased. However, the estimate of 133 ft^3 per cow-day is based on only three observations whereas the estimate of 109 ft^3 per cow-day is based on 11 observations and appears to be a more reliable estimate.

Composition—As shown in Table 4-5, there was little variation in the composition of the biogas produced during the course of this study. Methane and carbon dioxide contents averaged 55.9±2.1 and 43.8±2.1 percent by volume, respectively. The low NH_3 concentration of 0.000347 percent by volume confirms the conclusion, based on mass balance results, that NH_3 desorption during anaerobic digestion of dairy manure is nominal. However, the concentration of hydrogen sulfide found in the Gordondale Farms biogas, 0.310 percent by volume, indicates that emissions of oxides of sulfur during biogas combustion are potentially significant._

Based on a methane content of 55.9 percent (Table 4-5) and biogas production rate of 93,501 ft^3 per day, the rate of methane production from the Gordondale Farms anaerobic digester was 52,267 ft^3 per day. Thus, the rates of biogas and methane production are 24.22 and 13.54 ft^3 per lb TVS destroyed, respectively. Anaerobic digestion of municipal wastewater treatment sludges (biosolids) typically yields between 12 and 18 ft^3 of biogas per lb TVS destroyed (Metcalf and Eddy, Inc., 1991).

Theoretically, the destruction of one pound 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 38.5 percent reduction in COD in the Gordondale Farms anaerobic digester (Table 4-2) is equivalent to a 4,107 lb per day (Table 4-3) reduction in BOD_u and the production of 23,081 ft^3 of methane per day. However, the observed rate of methane production from the Gordondale digester was 12.73 ft^3 per lb COD destroyed with no apparent explanation for this inconsistency.

Biogas Utilization

During this 12-month study, Alliant Energy generated and delivered to their transmission system 2,438±583 kWh per day of electricity, which translates into 3.25±0.78 kWh per cow-day with an on-line efficiency of 97.3 percent. This rate of electricity generation is about 88 percent of the design value estimate by the system designer, GHD, Inc. of 3.7 kWh per cow-day and translates into the use of only 73 percent of the rated capacity of the generator set (140 kWh). Because of the low capacity utilization, only 29.8 kWh were generated per 1,000 ft^3 of biogas utilized, which translates into a thermal conversion efficiency of only 18 percent. 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).

After this study was started, it was learned that the performance of the engine-generator set also had been below expectations during the previous year (2003), with electricity generation averaging 2,499±858 kWh per day. Although several attempts to identify the cause of the substandard performance (including the removal of the Roots gas meter), none were successful until spark plugs were replaced on 12 October 2004. When replacement occurred, the electrical output immediately increased to near its rated capacity of 140 kW. From 12 October through the end of the study, the engine-generator set operated at an average of 3.86±0.15 kWh per cow-day with thermal efficiency of approximately 21 percent.

Waste Heat Recovery

One of the objectives of this study was to determine the quantity of waste heat being recovered from the engine-generator set that is being beneficially used for milking center water and space heating. However, physical constraints precluded this determination. It was possible, however, to determine the total quantity of waste heat available from the engine-generator set cooling system and exhaust gases and the fraction being used for digester heating and in milking center. Two Onicon, Inc. Model F-1100 BTU meters were used.

During the 12 months of this study, 680,416 x 10^4 BTUs, which translates into 2.309 x 10^4 BTUs per cow-day (assuming an average herd size of 805 cows), were recovered. Of this total, 574,934 x 10^4 BTUs were used beneficially for digester and milking center space and water heating with the remainder discharged to the atmosphere. The total BTUs recovered represent approximately 34 percent of the biogas energy being produced at Gordondale Farms.

Solids Separation

As mentioned earlier, Gordondale Farms uses a screw press separator to recover coarse solids from the digester effluent for on-farm use and sale as bedding. On a wet weight basis, an average of 14,415 lb per day of course solids is recovered before drainage of free moisture, and they contain an average of 4,123 lb of dry matter. Table 4-7 compares the characteristics of the digester effluent and the separated liquid and solid fractions.

As indicated in Table 4-7, the concentrations of TS and TVS in the separated liquid and solid fractions are similar. Conversely, the liquid fraction contains over 75 percent of the TKN and NH_4-N and almost two-thirds of the phosphorus and FS originally present in the digester effluent. Although the removal of nitrogen and phosphorus by solids separation at Gordondale Farms is significant, over 70 percent of these nutrients remain on the farm because the separated solids are used as bedding.

Although the separated solids at Gordondale Farms are not being composted-prior to on-farm use or sale, composting could provide an opportunity for sale as a mulch material or soil amendment. The organic carbon content of the separated solids can be estimated as approximately 55.5 percent of TVS (Haug, 1980 and Rynk *et al*., 1992), the carbon to nitrogen (C:N) ratio of the separated solids at Gordondale Farms is approximately 17.5:1. At this C:N ratio, nitrogen availability will not limit the rate of stabilization but some ammonia will be emitted by volatilization. A C:N ratio of 30 to 35:1 generally is considered optimal for minimizing nitrogen loss without limiting the rate of stabilization.

SECTION 5

DISCUSSION

In a previous AgSTAR study, (Martin 2003) evaluated the performance two manure management systems in a cold climate (central New York): one system with anaerobic digestion (AA Dairy) and one without (Patterson Farms). The AA Dairy anaerobic digester is a conventional plug-flow digester. Where feasible, this discussion compares the performance and operating parameters of the modified plug-flow digester at Gordondale Farms with the more conventional plug-flow design at AA Dairy.

Manure Production and Characteristics

As shown in Table 5-1, there are both similarities and significant differences the production rate and composition of manure among Gordondale Farms, AA Dairy, and Patterson Farms. Probably the most important similarity is in the TVS excretion rates and the most important difference is in COD excretion rates, with the rate for Gordondale Farms being approximately two-thirds of the rates for AA Dairy and Patterson Farms. The reason for this difference is not apparent. It does, however, at least partially explain the previously discussed inability to relate COD destruction with methane production based on the previously discussed theoretical ratio of 5.62 ft^3 of methane generated per lb of COD destroyed. Conversely, the TVS:COD ratio for the Gordondale Farms manure closely agrees with the ratio based on the USDA (1992) standard reference value (See Table 4-1), whereas the ratios for the AA Dairy and Patterson Farms manures are substantially higher. The other difference of significance is the higher phosphorus excretion rate for Gordondale Farms, which is statistically significant and probably is a reflection of a difference in feeding practices. The higher volume of manure produced per cow-day at Gordondale Farms is due to the inclusion of milking center wastewater, which is not co-mingled with manure at AA Dairy or Patterson Farms before storage.

Anaerobic Digester Performance and Biogas Utilization

Waste Stabilization—The Gordondale Farms plug-flow digester was designed to operate at a HRT of 22 days but operated at an average HRT of 29 days during this study. At this HRT, TVS and COD reductions averaged 39.6 and 38.5 percent, respectively (Table 4-2). As shown in Table 5-2, the TVS reduction at Gordondale Farms was substantially higher than that observed in a conventional plug flow digester at AA Dairy, whereas the COD and TVA reductions were-similar (Martin, 2003). This is a reflection of the difference in the readily biodegradable fraction of TVS as discussed below.

The results of the batch biodegradability study indicated that 47 percent of Gordondale Farms manure TVS are readily biodegradable in an engineering context with the remaining 53 percent being refractory. Thus, it appears that 84 percent of the biodegradable volatile solids (BVS) in Gordondale manure are being degraded at the digester HRT of 29 days. The linear regression relationship developed from the batch biodegradability data (Equation 1) also suggests that reducing digester HRT to the design value of 22 days would reduce TVS reduction from 39.6 to 33.7 percent, a decrease of 15 percent. Therefore, it appears any significant increase in herd size beyond 860 cows could begin to measurably reduce the degree of waste stabilization. It should be noted that the biodegradable fraction of Gordondale Farms TVS is substantially higher than the previously reported value of 30 percent for AA Dairy TVS (Martin, 2003).

$$TVS_t/TVS_0 = 0.31\ (1/TVS_0 * t) + 0.53 \qquad (1)$$

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

The 39.6 percent reduction in TVS observed in this study is comparable to the 37.6 percent reduction reported by Morris (1976) at a HRT of 30 days in a bench-scale anaerobic digester. The 41.9 percent reduction in COD is essentially the same as the 40.6 percent reduction also reported by Morris. The reduction in TVS observed in this study also is similar to the 40.6 percent reduction reported by Jewell *et al*. (1991) for a 65-cow plug-flow digester at a HRT of 30 days.

<u>Pathogen Reduction</u>—As also shown in Table 5-2, the reduction in the density of the fecal coliform group of indicator organisms at Gordondale Farms was somewhat less than the reduction observed at AA Dairy. However, the reduction still exceeded 99 percent with over a 90 percent reduction in the density of the fecal streptococcus group of indicator organisms. Thus, it seems reasonable to conclude that a significant reduction of any pathogens present including *M. avium paratuberculosis*, the pathogen responsible for chronic, contagious enteritis in cattle and possibly Crohn's disease in humans, also is occurring (Merck and Company, Inc., 1998).

<u>Biogas Production</u>—The mean rate of biogas production observed in this study was 109 ft^3 per cow-day. This is significantly higher than the biogas production rate of 78 ft^3 per cow-day observed in the evaluation of the conventional plug-flow digester at AA Dairy (Martin, 2003) and is consistent with the higher reduction in TVS observed in this study (Table 5-2). In addition, the rates of biogas and methane production per lb of TVS destroyed at Gordondale are somewhat higher than those observed at AA Dairy (Table 5-3), suggesting some difference in TVS composition. However, the AA Dairy biogas had a higher methane content, 59.1 percent versus 55.9 percent in the Gordondale Farms biogas.

If a future increases in herd size at Gordondale Farms reduce the digester HRT to the design value of 22 days, the estimated reduction in TVS destruction-also would reduce the biogas production rate by 15 percent to approximately 93 ft^3 per cow-day. However, total biogas production would increase to 98,766 ft^3 per day. This is based on an assumed increase in herd size to approximately 1,060 cows with no change in digester influent volume per cow-day.

Biogas Utilization—The full potential for generating electricity from the biogas produced at Gordondale Farms was not being realized during this study. Even at the peak output, which was observed during the last two months of this study, the 21 percent thermal efficiency for converting biogas to electricity is relatively low. Therefore, a greater potential for generating electricity at Gordondale Farms exists. If the thermal efficiency of converting biogas to electricity could be increased to 30 percent, which Koelsch and Walker (1981) suggested to be feasible, electrical output could be increased to 5.59 kWh per cow-day, which is close to output of 6.25 kWh per cow-day anticipated by the system designer, GHD, Inc. Achieving this potential, however, would require an increase in generating capacity to 200 kW.

Methane Emissions—Gordondale Dairy is estimated to be reducing methane emissions by 221 lb per cow-year through biogas production, capture, and utilization. This estimate was made using the methodology currently employed by the U.S. Environmental Protection Agency for developing the annual inventory of U.S. greenhouse gas emissions and sinks (U.S. Environmental Protection Agency, 2005) and the following assumptions. Based on the results obtained in this study, maximum methane producing capacity (B_0) was assumed to be 0.32 m^3 per kg of TVS excreted. This is significantly higher than the standard reference value for dairy cattle of 0.24 m^3 per kg of TVS excreted (U.S. Environmental Protection Agency, 2005 and Intergovernmental Panel on Climate Change, 2000). In addition, the methane conversion factor (MCF) for liquid/slurry manure storage facilities in Wisconsin of 22.4 percent was assumed. This translates into a total reduction of approximately 95 tons per year for the current 860-cow milking herd. Because methane has 21 times the heat trapping capacity of carbon dioxide (U.S. Environmental Protection Agency, 2005), the reduction in methane emission is equivalent to an emission reduction of 1,996 tons of carbon dioxide per year or 3.03 tons per cow-year.

However, the reduction in greenhouse gas emissions due to biogas production and utilization at Gordondale Farms 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. About 2,249 lbs of carbon dioxide are emitted per megawatt-hour (MWh) of electricity generated from coal (Spath *et al*., 1999). Accordingly, the estimated 957,655 kWh of electricity generated by Gordondale Farms using biogas potentially reduces fossil fuel derived carbon dioxide emissions by an additional 1,077 tons per year or 1.33 tons per cow-year. With operation of the engine-generator set at its rated capacity of 140 kW and an on-line efficiency of 97 percent, these potential reductions would increase to 1,338 tons per year or 1.56 tons per cow-year. In addition, even greater reductions would be realized if the thermal efficiency of the conversion of biogas to electricity could be improved. In this analysis, the carbon dioxide emissions from biogas combustion are not considered to contribute to a buildup of greenhouse gases since the carbon dioxide emissions are not derived from a sequestered carbon source. Rather, this emission 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.

Separator Performance

Gordondale Farms uses a screw press separator to separate coarse solids from the anaerobic digester effluent for on-farm use and sale as a bedding material. As shown in Table 5-4, separation of coarse solids from the Gordondale the AA Dairy anaerobic digester effluents removed generally similar fractions of all of the parameters listed except total phosphorus. The percentage of phosphorus removed at Gordondale was substantially higher. This suggests that the Gordondale manure contained less soluble phosphorus as a percentage of total phosphorus.

Economic Analysis

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.

Capital Cost—Gordondale Farms estimates that they have invested $550,000 in their anaerobic digestion/biogas production system. This investment includes the digester and all associated equipment and structures. However, the system was partially constructed by the farm owners. Based on an estimate of $650,000 for a turnkey system provided by the project designer and builder, GHD, Inc., the partial construction by farm owners reduced the capital cost by $100,000. These cost estimates exclude the cost of the engine-generator set, which is owned and operated by Alliant Energy. The installed cost of the engine-generator set was $198,000 of which $160,000 was for the engine-generator set and interconnection. The remaining $38,000 was the cost of installation, which included labor and materials. Based on the design herd size of 750 cows and including the cost of the engine-generator set, the capital cost of the Gordondale Farms system was $997 per cow and would have been $1,131 per cow for a turnkey system. However, based on the current herd size of 860 cows, these cost have been reduced to $870 and $986 per cow, respectively.

Value of Electricity Generated—Alliant Energy pays Gordondale Farms flat rate of $0.015 per kWh of electricity generated. If the engine-generator set operates at its rated capacity of 140 kW, the potential income from biogas production is $18,396 per year. Although Alliant's engine-generator set has not operated at its rated capacity except during the last two and one-half months of 2004, Gordondale Farms has not been penalized for the reduced generator output and has received payment for the biogas delivered based on the 140 kW rated capacity of the engine-generator set. If Gordondale Farms owned the engine-generator set, they would be paid $0.06 per kWh delivered to Alliant Energy, which would increase income to $73,584 per year. To maintain the viability of agriculture in their service area, Alliant Energy pays farmers delivering electricity produced from biogas to their grid $0.06 per kWh. -

Annual Operation and Maintenance Costs—Because the digester system at Gordondale Farms has been in operation only since March 2002, 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. Because of the simplicity of the anaerobic digestion/biogas production component of these systems, essentially all of the operation and maintenance costs are associated with engine-generator set operation. Since Gordondale Farms does not own the engine-generator set, current operation and maintenance costs most likely are not reducing farm income significantly. -

Economic Viability—The attractiveness of any investment generally depends on the ability to generate income sufficient to recover capital at a rate of return that is competitive with other investment opportunities. If, however, odor control or some other benefit provided by anaerobic digestion is necessary to continue farm operation, an acceptable rate of return would be somewhat less than other investment alternatives if the general farm operation remains profitable.

As the system was operated during this study, the income produced from the sale of biogas to Alliant Energy was $18,396 per year with insignificant operation and maintenance costs. With income of only $0.015 per kWhr, the digester would not be economically viable without considering the other income generated by the manure management system. The additional income includes an estimated $60,000 per year in avoided bedding costs and an estimated income of $8,600 per year from the sale of excess separated solids. With this overall income of $86,996, the simple payback period for recovering the invested capital is 6.3 years.

While owning and operating the engine-generator set would have increased Gordondale Farms capital investment to $748,000, the additional net income from the sale of electricity would reduce the time to recover the capital invested without consideration of the value of the separated solids to 13.6 years. When the value of these solids is included, the simple payback period decreases to six years.

If the Gordondale Farms system was financed over a 20-year period at an 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 conditions, the net income would be $35,082 per year or a total of $701,640 over the estimated 20-year life of the system. Purchasing and operating the engine-generator set would increase net income to $53,184 per year or a total of $1,063,680 over the life of the system assuming a reliable output of 140 kW could be realized.

Because the fraction of recovered waste heat that was being used for milking center space and water heating in place of a conventional fuel such as propane could not be determined, the monetary value of this source of heat energy could not be estimated. However, it appears to be significant. If only five percent of the total amount waste heat that is being used for digester heating and in the milking center is being used in the milking center, the avoided cost for propane at $1.70 per gal is approximately $5,600 per year.

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 while concurrently producing a significant source of income. It should be noted, however, that the economic attractiveness of anaerobic digestion with biogas utilization at Gordondale Farms is due, at least partially, to the relatively high fraction of total volatile solids (47 percent) that are readily biodegradable. 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 would be decreased rather than enhanced.

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 assuming the efficiency of converting biogas to electricity can be increased to about 30 percent. This system modification would increase electricity generated by about 43 percent with a somewhat lower but still significant increase in net income.

REFERENCES

American Public Health Association. 1995. Standard Methods for the Examination of Water and Wastewater, 20th Ed. A.D. Eaton, L.S. Clescrei, and A.E. Greenberg, Eds. American Public Health Association, Washington, DC.

ASTM International. 1990. Standard Practice for Analysis of Reformed Gas by Gas Chromatography, ASTM D1946-90. ASTM International, West Conshohocken, Pennsylvania.

Haug, R.T. 1980. Compost Engineering: Principles and Practice. Ann Arbor Science Publishers, Ann Arbor, Michigan.

Intergovernmental Panel on Climate Change. 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, J. Penman, D. Kruger, I. Galbally, T. Hiraishi, B. Nyenzi, S. Emmanul, L. Buendia, R. Hoppaus, T. Martinsen, J. Meijer, K. Miwa, and K. Tanabe (Eds). Institute for Global Strategies, Japan.

Jewell, W.J., R.M. Kabrick, S. Dell'Orto, K.J. Fanfoni, and R.J. Cummings. 1981. Earthen-Supported Plug-flow Reactor for Dairy Operations. In: Methane Technology for Agriculture. Northeast Regional Agricultural Engineering Service, Ithaca, New York. pp. 1-24.

Koelsch, R. and L.P. Walker. 1981. Matching Dairy Farm Energy Use and Biogas Production. In: Methane Technology for Agriculture. Northeast Regional Agricultural Engineering Service, Ithaca, New York. pp. 114-136.

Martin, J.H., Jr. 2003. Comparison of Dairy Cattle Manure Management with and without Anaerobic Digestion and Biogas Utilization. Final Report submitted by the Eastern Research Group, Inc., Boston, Massachusetts to the AgSTAR Program, U.S. Environmental Protection Agency, Washington, DC.

Martin, J.H., Jr. and R.C. Loehr. 1976. Demonstration of Aeration Systems for Poultry Wastes. EPA-600/2-76-186. U.S. Environmental Protection Agency, Athens, Georgia, 152 pp.

Martin, J.H., Jr., R.C. Loehr, and R.J. Cummings. 1981. The Oxidation Ditch as a Dairy Cattle Waste Management Alternative. In: Livestock Waste: A Renewable Resource. American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 346-349.

Merck and Company, Inc. 1998. The Merck Veterinary Manual, Eighth Edition, S.E. Aiello, Ed. Merck and Company, Inc., Whitehouse Station, New Jersey.

Metcalf and Eddy, Inc. 1991. Wastewater Engineering: Treatment, Disposal, and Reuse. McGraw-Hill Publishing Company, New York, New York.

Morris, G.R. 1976. Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Evaluation. Unpublished M.S. Thesis. Cornell University, Ithaca, New York. 193 pp.

Nelson, C. and J. Lamb. 2002. Final Report: Habenschild Farms Anaerobic Digester Updated! The Minnesota Project, St. Paul, Minnesota. 35 pp.

Rynk, R., M. van de Kamp, G.B. Willson, M.E. Singley, T.L. Richard, J.J. Kolega, F.R. Gouin, L. Laliberty, Jr., D. Kay, D.W. Murphy, H.A.J. Hoitink, and W.F. Brinton. 1992. On-Farm Composting Handbook. NRAES-54. Northeast Regional Agricultural Engineering Service, Ithaca, New York.

Snedecor, G. W. and W.G. Cochran. 1980. Statistical Methods, 7th Ed. The Iowa State University Press, Ames, Iowa.

Spath, P.L., M.K. Mann, and D.R. Kerr. 1999. Life Cycle Assessment of Coal-Fired Power Stations. Report No. TP-570-25119. National Renewable Energy Laboratory, Golden, Colorado.

Steel, R.G.D. and J.H. Torrie. 1980. Principles and Procedures of Statistics, 2nd Ed. McGraw-Hill Book Company, New York, New York.

Tietjen, C. 1975. From Biodung to Biogas—Historical Review of European Experience. In: Energy, Agriculture, and Waste Management, W.J. Jewell Ed. Ann Arbor Science Publishers, Inc. Ann Arbor, Michigan. pp. 247-259.

U.S. Department of Agriculture. 1992. Agricultural Waste Management Field Handbook, rev 1, July 1996. Natural Resources Conservation Service, Washington, DC.

U.S. Environmental Protection Agency. 1983. Methods for Chemical Analysis of Water and Wastes. PB84-128677. Environmental Monitoring and Support Laboratory, Cincinnati, Ohio.

U.S. Environmental Protection Agency. 2005. Inventory of U.S. Greenhouse gas Emissions and Sinks: 1990-2003. EPA 430-R-05-003. Office of Atmospheric Programs, Washington, DC.

Wright, P. and S.P. Perschke. 1998. Anaerobic Digestion and Wetland Treatment Case Study: Comparing Two Manure Odor Control System for Dairy farms. ASAE Paper No. 98-4105, American Society of Agricultural Engineers, St. Joseph, Michigan. 11 pp.

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

Parameter	**Gordondale Farms**	**USDA (1992)**
Volume, ft^3/cow-day	3.04	1.82
Total solids, kg/cow-day	7.6	6.4
Total volatile solids, kg/cow-day	5.8	5.4
Fixed solids, kg/cow-day	1.8	1.0
Chemical oxygen demand, kg/cow-day	6.0	5.7
Total Kjeldahl nitrogen, kg/cow-day	0.30	0.29
Total phosphorus, kg/cow-day	0.067	0.044

Table 4-2. Gordondale Farms anaerobic digester performance summary, mg/L*.

Parameter	Influent	Effluent	Reduction, %
Total solids	88,100[a]±17,200	56,900[b]±7,800	35.4
Total volatile solids	67,200[a]±11,100	40,600[b]±8,500	39.6
Fixed solids	20,900[a]±7,300	14,400[b]±4,400	31.1
Chemical oxygen demand	69,923[a]±19,229	43,000[b]±8,333	38.5
Soluble chemical oxygen demand	7,998[a]±5,187	3,298[b]±2,222	58.8
Total volatile acids	5,725[a]±1,314	700[b]±1,238	87.8
Total Kjeldahl nitrogen	3,478[a]±719	3,254[a]±663	—
Organic nitrogen	1,782[a]±621	1,135[b]±557	36.3
Ammonia nitrogen	1,696[a]±243	2,119[b]±231	+24.9†
Total phosphorus	783[a]±228	715[a]±178	—
Soluble orthophosphate phosphorus	7.3[a]±4.3	4.7[b]±2.1	64.4
pH	7.6[a]±0.3	8.2[b]±0.2	—

*Means in arrow with a common superscript are not significantly different ($P<0.01$, $n=24$).
†Increase in concentration.

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

Parameter	Reduction, lb/day
Total solids	4,760
Total volatile solids	3,860
Chemical oxygen demand	4,107
Soluble chemical oxygen demand	717

Table 4-4. Comparison of Gordondale Farms anaerobic digester $\log_{10}$ influent and effluent densities of the fecal coliform and fecal streptococcus groups of bacteria.

Parameter	Influent	Effluent	Reduction
Fecal coliforms, $\log_{10}$ CFU/100 ml	$8.9^{a}\pm1.4$	$6.6^{b}\pm1.1$	2.3
Fecal streptococcus, $\log_{10}$ CFU/100 ml	$8.6^{a}\pm1.2$	$7.3^{b}\pm1.2$	1.3

Table 4-5. Gordondale Farms biogas composition.

Parameter	% by volme
Methane	55.9*±2.1
Carbon dioxide	43.8*±2.1
Hydrogen sulfide	0.310†
Ammonia	0.000347†

*n=24
†n=1

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

Parameter	Biogas	Methane
$ft^3/lb\ TVS_D$	24.22	13.54
$ft^3/lb\ COD_D$	22.77	12.73

Table 4-7. Comparison of the characteristics of the Gordondale Farms anaerobic digester effluent (separator influent) with the separated liquid and solid fractions.

Parameter	Digester effluent	Separated liquid	Separated solids
Total solids, g/L	56.9	33	286
Total volatile solids, g/L	41.9	23	210
Fixed solids, g/L	15	10	76
Total Kjeldahl nitrogen, mg/L	3,254	3,300	6,900
Organic nitrogen, mg/L	1,135	1,287	4,462
Ammonia nitrogen, mg/L	2,119	2,046	2,402
Total phosphorus, mg/L	715	495	2,888

Table 4-8. Distributions of the constituents of Gordondale Farms anaerobic digester effluent following separation, % by weight.

Parameter	Liquid fraction	Solid fraction
Total solids	52.5	47.5
Total volatile solids	51.0	49.0
Fixed solids	62.3	37.7
Total Kjeldahl nitrogen	82.3	17.7
Organic nitrogen	73.4	26.6
Ammonia nitrogen	89.1	10.9
Total phosphorus	62.2	37.8

Table 5-1. Comparison of the Gordondale Farms rates of production of manure and its various constituents with those of two upstate New York dairy farms.

Parameter	Gordondale Farms	AA Dairy*	Patterson Farms*
Volume, ft^3/cow-day	3.04	2.10	2.35
Total solids, kg/cow-day	7.6	6.7	7.1
Total volatile solids, kg/cow-day	5.8	5.7	5.8
Fixed solids, kg/cow-day	1.8	1.0	1.3
Chemical oxygen demand, kg/cow-day	6.0	9.1	9.4
Total Kjeldahl nitrogen, kg/cow-day	0.30	0.28	0.28
Total phosphorus, kg/cow-day	0.067	0.048	0.045

*Martin, 2003.

Table 5-2. Comparison of the performance of the Gordondale Farms and the AA Dairy anaerobic digesters with respect to waste stabilization and indicator organism reduction.

Parameter	Gordondale Farms	AA Dairy*
Total solids, %	35.4	25.1
Total volatile solids, %	39.6†	29.7
Chemical oxygen demand, %	38.5	41.9
Soluble chemical oxygen demand, %	58.8	30.0
Total volatile acids, %	87.8	86.1
Fecal coliforms, $\log_{10}$	2.3	2.8
Fecal streptococcus, $\log_{10}$	1.3	—

*Martin, 2003.

†A result of the higher total volatile solids biodegradability.

Table 5-3. Comparison of rates of biogas and methane production and biogas methane content observed at Gordondale Farms and AA Dairy.

Parameter	Gordondale Farms	AA Dairy*
Biogas, ft^3/lb TVS destroyed	24.22	20.81
Methane, ft^3/lb TVS destroyed	13.54	12.30
Methane, % by volume	55.9	59.1

*Martin, 2003.

Table 5-4. Comparison of percentages of anaerobic digester effluent constituents recovered in the solid fraction of screw press separator effluent at Gordondale Farms with percentages recovered at AA Dairy, % by weight.

Parameter	Gordondale Farms	AA Dairy*
Total solids	47.5	50
Total volatile solids	49.0	56.1
Fixed solids	37.7	26.3
Total Kjeldahl nitrogen	17.7	19.1
Organic nitrogen	26.6	22.8
Ammonia nitrogen	10.9	15.6
Total phosphorus	37.8	22.1

*Martin, 2003.