FINAL

An Assessment of the Performance of the Colorado Pork, LLC. Anaerobic Digestion and Biogas Utilization System

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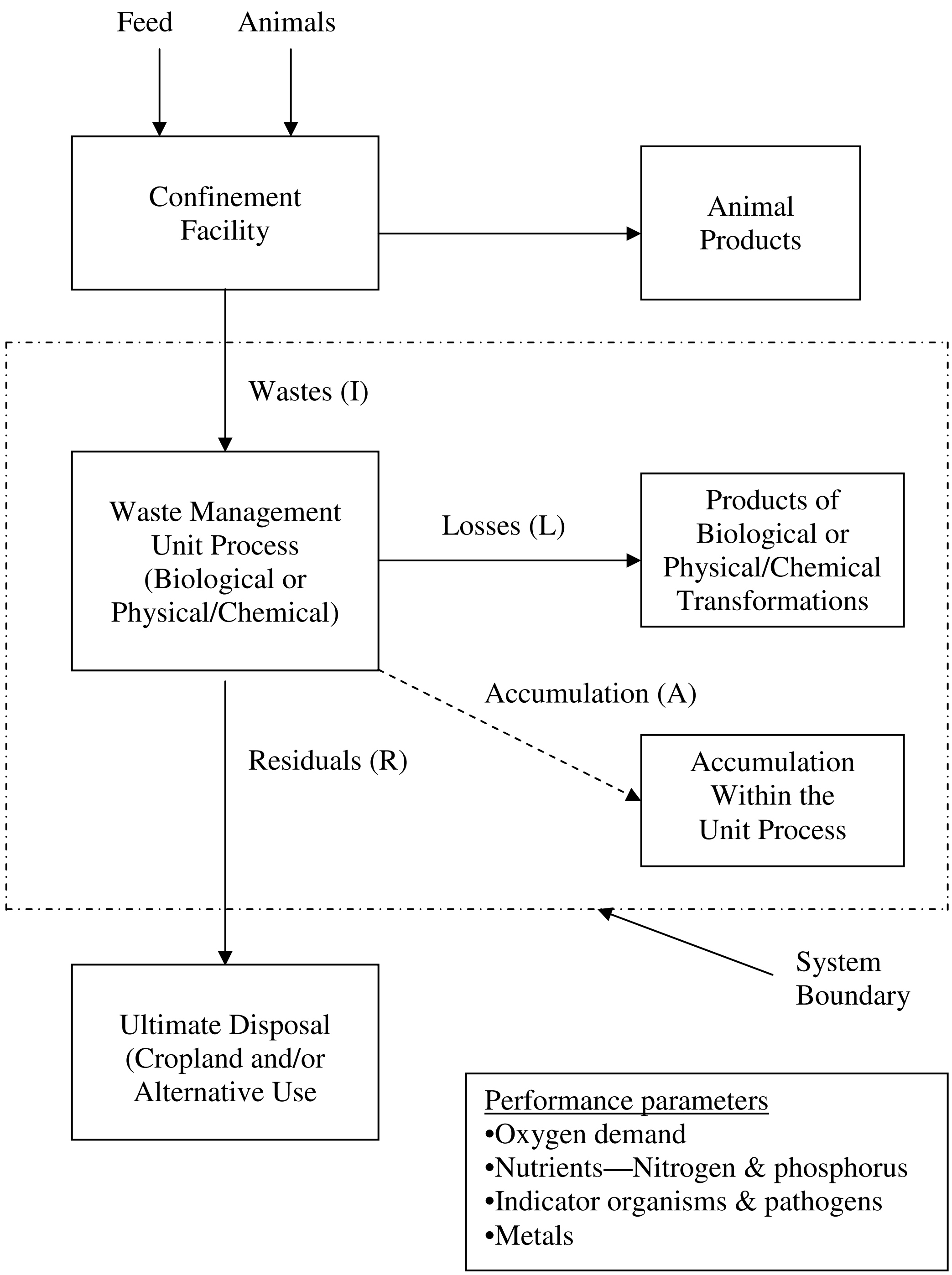
PREFACE

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.

This report was submitted simultaneously to Mr. Kurt Roos, AgSTAR Program, U.S. Environmental Protection Agency, Washington, DC.



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

Introduction

This report presents an assessment of the performance of the mesophilic intermittently mixed anaerobic digester used for swine manure stabilization and biogas production at Colorado Pork, LLC. (CP), Lamar, Colorado. Also presented is an assessment of the use of the biogas captured to generate electricity. These assessments of performance are based on data provided by the State of Colorado Governor's Office of Energy Management and Conservation (OEMC). Southeast Land and Environment (SELE), Lamar, Colorado was responsible for the planning and execution of the study that produced these data. Data collection began in late April 2000 and ended in early April 2001.

CP is a 5,000 sow farrow-to-wean operation with 1,200 gilts being raised as sow replacements in environmentally controlled buildings with pull-plug pits. The anaerobic digester is an in-ground concrete tank with an operating volume of 500,000 gallons. The digester is operated as a fill and draw reactor on a 24-hour cycle with two 30 to 45 minute mixing episodes ever 24 hours. Flow through digester decreased over the 12 months of data collection and averaged 13,846±2,433 gallons per day. Biogas is captured in a flexible reinforced plastic collection dome attached to the top of the digester. The digester is heated to maintain a temperature of approximately 102 °F using cooling system waste heat from an 80 kW engine-generator set used to generate electricity from the biogas produced. Digester effluent is discharged to an approximately seven-acre storage and evaporation pond.

During the 12 months of data collection to assess the performance of this system, anaerobic digestion in combination with biogas utilization provided the following benefits:

- Reduction of odors to below Colorado's Amendment 14 detection threshold maximum compliance level of 6,000;

- Reduction of methane emissions on a carbon dioxide equivalent basis by at least 3,022 tons per year;

- Potential reduction of fossil fuel derived carbon dioxide emissions by 409 tons per year;
- Reduction of hydrogen sulfide emissions by 5,902 lb per year;
- Generation of 342,414 kWh of electricity with an estimated gross value of $22,907 for onsite use; and
- Reduction of water pollution potential through the conversion of oxygen demanding organic compounds to biogas and a reduction in an indicator of pathogenic microorganism density.

Odor Reduction

Although odor threshold levels prior to anaerobic digester operation were not available, the average of seven determinations of odor threshold level adjacent to the digester during the 12 months of data collection was 2,842. Adjacent to the storage and evaporation pond, the average of eight determinations was 5,589. Both averages were below the maximum compliance level of 6,000. Thus, it can be concluded that the objective of odor reduction was achieved.

Greenhouse Gas Emissions

The estimate of methane emissions reduction, on a carbon dioxide equivalent basis, of 3,022 tons per year is somewhat of an underestimate because only the volume of biogas utilized to generate electricity was measured. Biogas disposed of by flaring when the engine-generator set was out of service or when onsite demand for electricity resulted in a demand for biogas that was less than the rate of production was not measured. Therefore, total biogas production and the total reduction in methane emissions is unknown but exceeded the carbon dioxide equivalent of 3,022 tons per year. This estimate is based on the reasonable assumption that methane emitted from a conventional anaerobic lagoon designed for the same number of animals will be equal to the methane produced in the CP digester.

When the carbon dioxide emitted during the combustion of methane to generate electricity is considered, the net reduction of methane emissions, on a carbon dioxide basis, is reduced to 2,878 tons per year. However, the potential reduction of fossil fuel derived carbon dioxide emissions resulting from the use of the electricity generated from biogas is estimated to be 409 tons per year. Therefore, a total reduction in greenhouse gas emissions of at least 3,287 tons per year on a carbon dioxide equivalent basis was being realized.

Hydrogen Sulfide Emissions

The biogas produced by the CP anaerobic digester had a sulfur content of 0.556 lb per 1,000 ft^3 (5,786 ppm). Essentially all of this sulfur was in the form of hydrogen sulfide. Therefore, combustion of this biogas to generate electricity or by flaring reduced potential emission of hydrogen sulfide by at least an estimated 5,902 lb per year. This probably contributed significantly to the level of odor control that was realized.

Biogas Utilization

Due to an atypically high frequency of engine-generator set mechanical and electrical problems, this unit was out of service for 32 days in the 12 month period of data collection at CP. This resulted in an on-line efficiency for the engine-generator set of 90.5 percent and a rate of electricity generation of 342,414 kWh per year. For the 333 days that the engine-generator set was in-service, the on-line efficiency was 94.8 percent. At this on-line efficiency, which exceeds that of a typical coal-fired electrical generating station, the rate of electricity generation would be 363,905 kWh per year, which seems to more accurately characterize the potential of this system to generate electricity and income under current operating conditions.

It is possible, however, that the potential for biogas utilization to generate electricity is even greater assuming the volume of biogas being disposed of by flaring is significant. If so, the current rate of generating electricity is being constrained by the magnitude of and the variability in the demand directly connected to the engine-generator set. Because there was no intertie between CP and the local electric utility, Southeast Colorado Power, at the time of this study, CP only could utilize biogas-generated electricity onsite. Therefore, biogas utilization was limited by electrical demand directly connected to the engine-generator set. After this study was completed, interconnection with Southeast Colorado Power (SCP) was established providing for sale of biogas-generated electricity when the rate of generation exceeds onsite demand.

The relatively low current thermal efficiency of the conversion of biogas energy to electrical energy, 22 percent, is another apparent constraint on biogas utilization at CP. This low efficiency is a reflection of the only 52 percent utilization of the engine-generator set capacity of 80 kW. With operation of the engine-generator set at or near rated capacity, the thermal efficiency of the conversion of biogas energy to electrical energy should be about 30 percent. This would increase the rate of electricity generation from the volume of biogas currently being utilized to 496,234 kWh per year. However, it is unclear if such an increase in thermal conversion efficiency could be realized without knowledge of total biogas production. A meter recently was installed at CP to measure and record total biogas production, and this information will be available in the near future. If sufficient biogas were available, an interconnection with SCP probably would also be necessary to operate the engine-generator set at or near rated capacity.

Waste Stabilization

Materials balances based on average digester influent and effluent concentrations and the average flow of 13,846 gallons per day, indicate that substantial reductions in total volatile solids (TVS), 5-day biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD) were occurring in the CP anaerobic digester. The calculated mass reductions in TVS, BOD_5, and COD are 64.0, 81.9, and 67.6 percent, respectively. In addition, a reduction somewhat greater than 99.9 percent in the density of the fecal coliform group was being realized. This suggests that significant reductions in densities of pathogens, when present, also were occurring. Therefore, the potential impact of the digester effluent on surface water quality is being substantially reduced.

However, it appears, based on fixed solids, total phosphorus, copper, and zinc balances, that significant settling and accumulation of particulate matter in the digester is occurring. Therefore, settling is partially responsible for the TVS, BOD_5, and COD mass reductions noted above. The accumulation of settled particulate matter in the CP digester is gradually increasing the solids retention time and probably is marginally increasing the microbially mediated reduction of complex organic compounds to methane. However, the accumulation of settled particulate matter also is gradually decreasing the active volume of the digester and therefore hydraulic retention time (HRT). If HRT falls below some critical value, process failure will occur and biogas production will essentially cease. Therefore, it appears that periodic removal of accumulated particulate matter from the CP digester will be necessary to maintain process stability.

The information necessary to estimate rate of accumulation of settled particulate matter and the necessary frequency of removal of accumulated particulate matter was not obtained during this study. However, Mattocks *et al.* (2002) indicated that some settling and accumulation of particulate matter was anticipated when the CP digester was designed. Measurement of the depth of accumulated particulate matter will be scheduled in the near future to resolve this issue.

Economic Viability

As noted above, the on-line efficiency of the CP engine-generator set during this 12-month study was 90.5 percent and the gross revenue realized from the biogas derived electricity generated and utilized onsite is estimated to be $22,907 per year. This estimate assumes a unit value of $0.0699 per kWh. However, the on-site generation and utilization of electricity at CP also has reduced the cost of electricity purchased from the local electric utility from $0.0699 to $0.04 per kWh, which provides an additional $14,919 per year in gross revenue due to anaerobic digestion with biogas utilization. With the assumption of an average $5,459 per year for operation and maintenance, estimated net revenue for the study period is estimated to be $32,367 per year.

However, the engine-generator set was out of service for several extended periods totaling 32 days during the study due to mechanical and electrical problems that can be considered atypical. For the remaining 333 days, on-line efficiency was 94.8 percent, which seems like a more objective basis to estimate typical gross and net revenues and economic viability. On this basis, gross and net revenues respectively would be $39,264and $33,805 per year.

Therefore, 10.9 years will be required to recover the $368,000 of capital invested in the anaerobic digester and engine-generator set if the time value of money is ignored. At an interest rate of seven percent, the recovery of invested capital over 20 years would require annual principal and interest payments of $34,736 per year. Therefore, anaerobic digestion with biogas utilization at CP appears to be currently reducing net farm income by an estimated $931 per year or $0.19 per sow confined. This translates into a return on capital invested of slightly less than seven percent with internal financing. Given the perceived need for odor control for CP to remain in operation, this appears to be a very reasonable cost given the capital cost of non-revenue generating alternatives to assure compliance with Colorado's odor control requirements. However, it appears, as discussed earlier, that opportunities for increasing the amount of electricity generated annually may exist. Therefore, an increase in annual net revenue and a reduction in the period for capital recovery or net annual cost appear possible if the volume of biogas disposed of by flaring was significant. In addition, there may be other options for increasing revenue.

SECTION 2

INTRODUCTION

Anaerobic digestion of swine manure with biogas capture and utilization has been demonstrated to be a technically feasible alternative to reduce odor problems associated with the management of these wastes. This process also reduces the emission of methane, a greenhouse gas, and the potential impact of these wastes on water quality through the reduction of oxygen demanding organic compounds and pathogenic microorganisms when present. Currently, two approaches are being utilized for the anaerobic digestion of swine manure. They are covered anaerobic lagoons, which are not heated, and heated digesters, which are modified versions of anaerobic digesters used widely for the stabilization of wastewater treatment sludges. One of the principal advantages of heated digesters is a constant rate of biogas production. This allows more economically efficient utilization of the biogas energy produced. With unheated covered lagoons, biogas production varies with seasonal changes in ambient temperature.

This report presents a characterization of the performance of an anaerobic digester for swine manure and the system utilized to generate electricity from the biogas captured at CP. This characterization of performance was based on data provided by OEMC. Southeast Land and Environment, Lamar, Colorado was responsible for the planning and execution of the study that produced these data. Data collection began in late April 2000 and ended in early April 2001. The Colorado Air Quality Control Division and CP were project cooperators. Support for the data collection effort was provided by the Western Regional Biomass Energy Program (WRBEP) through the OEMC with U.S. Department of Energy funds.

Section 3

Background

Site Description

CP is a 5,000 sow farrow-to-wean operation located in Lamar, Colorado, which is located in the southeastern corner of the state. The sows and 1,200 replacement gilts are housed in total confinement facilities with pull-plug pits under slatted floors for manure collection and temporary storage (Southeastern Land and Environment, 1999).

On 6 August 1999, an anaerobic digester was placed in operation at CP to address concerns of neighbors and the state of Colorado about the environmental quality impacts of the operation including odors and to reduce the cost of satisfying the farm's electricity requirements. In late September, a rate of biogas production necessary to maintain the design temperature in the digester of at least 95 °F was realized. Therefore, the digester was in operation for six months before data collection to assess system performance began in early April 2000.

Manure drained from the pull-plug pits enters the anaerobic digester through a 50,000-gallon influent collection and mixing tank. Manure flows from the pull-plug pits into this tank by gravity through an underground pipe network and is mixed using a chopper pump prior to discharge into the digester. The influent collection and mixing tank contains a staff gauge to determine and control the volume of manure added daily to the digester.

The digester is 65 ft wide by 80 ft long by 14 ft deep in-ground concrete tank with a total volume of 72,800 ft^3 and an operating volume is 66,836 ft^3 (500,000 gallons). The design value for daily digester influent volume and therefore hydraulic retention time (HRT) could not be obtained. However, it appears that the influent collection and mixing tank was designed to contain four days of flow from the pull-plug pits. This suggests a digester design flow of 12,500 gallons per day, which translates into a design HRT of 40 days. The digester is operated as a daily batch loaded, fill and draw reactor with effluent flow occurring in response to influent flow. Although this digester previously has been described as a complete mix digester (Moser and Mattocks, 2000), mixing is intermittent. There are two 30 to 45 minute periods of mixing each day with one occurring prior to the transfer of manure from the influent collection and mixing tank. Biogas produced is collected in a flexible reinforced plastic collection dome, which covers and is attached to the open top of the digester.

The biogas produced and collected is used to generate electricity with a reconditioned Caterpillar 3306 engine coupled to an 80 kW generator. Heat recovered in the form of hot water from the engine is used to heat the digester. During this study, only biogas used to fuel the engine-generator set was measured. When the engine-generator set was not in operation or when biogas production exceeded engine-generator set demand, biogas was automatically flared to control the pressure in gas collection dome.

During the study, there was no intertie between CP and SCP. Therefore, biogas utilization was limited by electrical demand directly connected to the engine-generator set. Because this demand was not constant, it was necessary to vary generator output by varying engine speed automatically to match variations in the directly connected load. Therefore, generator output and biogas utilization depended on the electrical load directly connected to the engine-generator set. The control system for the engine-generator set also had an automatic shut down feature to avoid electrical equipment damage resulting from imbalances between generator output and demand. After this study was completed, interconnection with SCP was established providing for sale of biogas-generated electricity when the rate of generation exceeds onsite demand.

Digester effluent flow is by gravity to an earthen storage structure, which has a compacted clay liner. The structure was designed as an evaporation pond with a sediment trap. Digester effluent is discharged into the south end of the sediment trap. The pond has a maximum storage capacity with one foot of freeboard of 12 million gallons (37.75 acre-feet). The anaerobic digester and biogas utilization system was designed and constructed by RCM Digesters, Inc., Berkley, California.

Because the ability of anaerobic digestion of swine manure to satisfy the requirements of Colorado’s Amendment 14 was unclear, CP’s anaerobic digester was designated as experimental by the Colorado Department of Public Health and Environment at the time of construction. Anaerobic digestion subsequently has been certified as method for Amendment 14 compliance. Amendment 14 sets limits on odors emitted from swine production facilities.

Sample Collection

Manure Sampling—The collection of data to characterize the performance of the CP anaerobic digestion-biogas utilization system, as indicated earlier, began in late April 2000 and ended in early April 2001. Manure samples were collected at three locations: 1) the influent collection and mixing tank (digester influent), 2) the effluent collection chamber (digester effluent), and 3) the effluent storage structure sequentially on the same day. Twenty-five sets of manure samples were collected. Sampling frequency was approximately every two weeks.

The samples collected from the influent collection and mixing tank were grab samples following the flushing of one of the pull-plug pits and after 30 minutes of mixing. Sampling depth was 12 inches below the liquid surface with four plastic sample containers (one 1 liter, two 250 ml, and one 125 ml) filled during each sampling episode.

Samples of the digester effluent were collected from the effluent collection chamber as influent was being pumped into the digester. The point of sample collection was at the point of discharge to the effluent storage structure. Again, four plastic sample containers (one 1 liter, two 250 ml, and one 125 ml) were filled during each sampling episode. Each container was filled from a composite of a minimum of three sub samples.

Samples of the effluent storage structure contents were collected at three locations at the north end of the sediment trap, which is approximately 600 feet from the point of digester effluent discharge. Each location was six feet from the end and at least 20 feet from the sides of the structure. As with the other two types of samples, four plastic sample containers (one 1 liter, two 250 ml, and one 125 ml) were filled during each sampling episode. Each container was filled from a composite of three sub samples from the three sample collection locations. All samples were collected at a depth of 12 inches below the liquid surface and were collected as digested effluent was being discharged from the effluent collection chamber.

All sample containers were provided by Midwest Laboratories, Inc., Omaha, Nebraska, and all samples were preserved by cooling to 4 °C until shipment for analysis. In addition, one of the two 250 ml sample containers filled at each sampling point contained sulfuric acid for sample preservation. The 125 ml sample containers were sterile and contained sodium thiosulfate. The reason for the presence of sodium thiosulfate in these sample containers is unclear. However, it appears that the sample containers used are intended for samples of potable water supplies for microbial analyses. In such samples, sodium thiosulfate is added to eliminate the effect of any free chlorine that may be present on the microbial population in the sample.

All manure samples were shipped in insulated coolers with containers of a frozen ice substitute to maintain sample temperature at approximately 4 °C. The one L and 250 ml samples were received by the laboratory performing the physical and chemical analyses on the second day after sampling. The 125 ml samples were received by the same laboratory for microbial density determinations on the day following sample collection.

Biogas Sampling—Biogas samples were taken from the pipeline delivering biogas to the engine-generator set. One L Tedlar gas collection bags were used. All biogas samples were received by the laboratory performing the gas analyses, Empact Analytical Systems, Inc., Brighton, Colorado, on the day following sample collection. Biogas sampling occurred on the same days as manure sampling. Therefore, there also were 25 biogas sampling events occurring at approximately two-week intervals.

Analytical Methods

Manure Samples—Each set of manure samples was analyzed by Midwest Laboratories, Omaha, Nebraska for those physical, chemical, and microbiological parameters listed in Table 3-1 using the analytical methods noted. Midwest Laboratories has a quality assurance/quality control (QA/QC) program to insure precision and accuracy of their analytical results. The plan of work for this study did not contain provisions to verify the effectiveness of Midwest Laboratories QA/QC program through submission of blind duplicate or spiked samples or both.

Biogas Analyses—Each biogas sample was analyzed for those characteristics listed in Table 3-2 by Empact Analytical Systems, Inc., Brighton, Colorado using the analytical methods noted. The other sulfur compounds included carbonyl sulfide/sulfur dioxide, methanethiol, ethanethiol, dimethyl sulfide, carbon disulfide, i-propanethiol, t-butanethiol, 1-propanethiol, methylethylsulfide, s-butaneethiol, i-butanethiol, thiophene, diethylsulfide, n-butanethiol, dimethyldisulfide, 2-methylthiophene, 3-methylthiophene, 2-ethylthiophene, methylethyldisulfide, dimethylthiophene, unidentified sulfurs, diethyldisulfide, benzothiophene, methylbenzothiophene, and dimethylbenzothiophene.

Empact Analytical Systems also has a quality assurance/quality control (QA/QC) program to insure precision and accuracy of their analytical results. The plan of work for this study also did not contain provisions to verify the effectiveness of Empact Analytical Systems QA/QC program through submission of blind duplicate or spiked samples or both.

Other Data Collected

Additional data of significance recorded daily: 1) cumulative hours of engine-generator set operation, 2) cumulative kWh of electricity generated, and 3) cumulative ft^3 of biogas utilized. Also influent volume, digester temperature, and flare operation, or absence thereof, were recorded daily.

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 (Snedecor and Cochran, 1980). To equalize variances, densities of fecal coliform bacteria 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 fecal coliforms was not always detected in digester effluent and storage structure samples.

Linear regression analysis (Snedecor and Cochran, 1980) was used to determine if digester influent or effluent TVS concentrations, and other characteristics by inference, or biogas utilization varied with time in response to variation in daily digester influent volume. For each regression, the null hypothesis that the slope was not significantly different statistically from zero was tested using the Student's t test.

SECTION 4

RESULTS AND DISCUSSION

Introduction

The CP anaerobic digester hydraulic loading rate varied from 11,000 gallons to 20,000 gallons per day over the 12-month period of data collection for the assessment of the system performance. During the first quarter, influent volume was 16,875±1,896 gallons per day. It decreased during the second quarter to 13,571±2,245 gallons per day and then further to 11,600±647 gallons per day during the third quarter. In the final quarter of the 12-month period of data collection, influent volume was a constant 12,000 gallons per day. The decrease in digester hydraulic loading rate over time was the result of a trial and error process to reduce water use to a level that would generate a constant 12,000 gallons per day of digester influent.

Because of this variation in hydraulic loading rate, characterization of system performance on a quarterly basis, as was done previously by Mattocks *et al*. (2002), did not seem justifiable due to the absence of true steady-state conditions. It did appear reasonable, however, to evaluate system performance on the basis of the total 12 month period of data collection given the absence of any statistically significant ($P<0.01$) relationships between influent and effluent characteristics and biogas production with time. Although linear regression analyses of the relationships between influent and effluent total volatile solids concentrations and biogas production with time revealed that all decreased slightly with time, the coefficients of variation (R^2 values) were less than 0.20 due to the degree of apparently random variation within each of these data sets. Consequently, the slopes of the regression relationships were found not to be statistically significant ($P<0.01$) from zero using the Student's t test (Snedecor and Cochran, 1980).

Therefore, this evaluation of the performance of the CP anaerobic digester is based on the average influent flow rate over the 12 months of data collection of 13,846±2,433 gallons per day. Because of the variation in the hydraulic loading rate with time, this assessment of system performance should be considered as an assessment under quasi steady-state conditions.

Waste Stabilization

As indicated in Table 4-1 by the magnitudes of the standard deviations, there was a considerable degree of variation in the physical and chemical characteristics of the influent to the CP anaerobic digester during the 12-month period of data collection. The source of this variation is unclear but is common due to difficulties in obtaining representative samples of animal wastes. However, the number of samples collected and analyzed (25) suggests that the calculated mean values are reasonable estimates of the true values. As also shown in Table 4-1, the variability in the physical and chemical characteristics of the digester effluent was considerably lower as would be expected given the theoretical average digester HRT of 36 days.

The comparisons of influent and effluent concentrations in Table 4-1 show that the CP anaerobic digester, on average, produced substantial reductions in TS, TVS, BOD_5, COD, VA, S, and FC during the 12 month period of the performance evaluation. The absence of statistically significant differences ($P<0.01$) between influent and effluent concentrations of TKN and NH_4-N indicates that NH_4-N volatilization in the digester and presence in the biogas produced is negligible. The reason or reasons for the decrease in the concentration of ON is unclear but merely may be a reflection of the degree of accuracy of the nitrogen determinations. TKN and NH_4-N concentrations only were estimated to the nearest 100 mg per L. ON was not determined analytically; it was calculated by subtracting the concentration of NH_4-N from the concentration of TKN.

Although the observed reductions in TS, TVS, BOD_5, COD, VA, and FC (Table 4-1) are consistent with expectations for anaerobic digestion under controlled conditions, the statistically significant ($P<0.01$) reductions in TP, Cu, and Zn are not and indicate that settling of particulate matter is occurring in the digester. The validity of this hypothesis is supported by the calculated FS reductions. This indicates that at least some fraction of the reductions in TS, TVS, BOD_5 and COD concentrations (Table 4-1) are due to accumulation in the digester and not the microbially mediated conversion to biogas.

In Table 4-2, the estimated mass reductions occurring in the CP anaerobic digester are summarized. These mass reductions are based on the assumed average daily flow through the digester of 13,846 gallons per day and the differences between influent and effluent concentrations are listed in Table 4-1. They reflect reductions in organic matter due to conversion to methane, carbon dioxide, and sulfur gases as well as accumulations in the digester due to settling. As noted earlier, the CP anaerobic digester is an unmixed reactor.

As shown in Table 4-2, an estimated 726 lb of FS are being retained daily in the digester given that FS, by definition, are not biodegradable. This is about 39 percent of the mass of FS entering the digester daily. Assuming the specific gravity relative to water of the accumulating FS is 2.5, FS density is 156 lb per ft^3. This translates into an accumulation rate, on a moisture free basis, of 1,699 ft^3 per year or approximately 2.5 percent of the digester operating volume of 66,850 ft^3. However, the actual volume occupied by the accumulating FS is probably significantly higher due to their moisture content, which is unknown. Thus, it is not possible to realistically estimate the actual rate of loss of digester operating volume due to the accumulation of FS. It can be stated, however, that the actual loss of digester operating volume is substantially higher than 2.5 percent per year.

The FS balance results that indicate FS are accumulating in the CP anaerobic digester also suggest that some accumulation of TVS and therefore COD also is occurring. Thus, it appears reasonable to hypothesize that only some fraction of the mass reductions in TVS, BOD_5, and COD based on the differences in the digester mean influent and effluent concentrations (Table 4-2) are due to the microbial mediated reactions responsible for biogas production. If total biogas production had been measured, the rates of accumulation of COD and TVS could be estimated with a reasonable degree of accuracy. 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. In addition, between 12 and 18 ft^3 of methane typically is produced during anaerobic digestion per lb of TVS destroyed (Metcalf and Eddy, 1991). It should be recognized that BOD_5, only represents a fraction of BOD_u. Therefore, the estimated reduction in BOD_5 presented in Table 4-2 is not comparable to the reduction in BOD_u.

Although the average rate of biogas production is unknown, it is possible to estimate the rates of accumulation of COD and TVS based on the rate of biogas utilization to provide a sense of the significance of TVS settling in the CP digester. This approach provides a worst-case estimate with the degree of error depending on the magnitude of the fraction of total biogas production that was flared. However, it may provide a reasonably accurate estimate if the fraction of total biogas production disposed of by flaring was relatively small.

The average rate of biogas utilization at CP was 27,370 ft^3 per day, and the average methane content was 67.9 percent. This translates into an average rate of methane utilization of 18,584 ft^3 per day. Assuming the conversion rate of 5.62 ft^3 of methane per lb of COD destroyed, 69 percent of the 4,794 lb of COD removed daily in the digester (Table 4-2) was removed through biogas production. At the conversion rate of 12 ft^3 of methane per lb of TVS destroyed, the fraction of daily mass TVS reduction (Table 4-2) was 68 percent, which is consistent with the 69 percent conversion of COD to biogas. This suggests that the rate of TVS accumulation in the CP anaerobic digester could be as high as 732 lb per day in addition to the 726 lb per day of FS accumulation.

Assuming the specific gravity relative to water of the accumulating TVS is one, TVS density is 62.4 lb per ft^3. This translates into an accumulation rate, on a moisture free basis, of 4,282 ft^3 per year or approximately 6.4 percent of the digester operating volume of 66,850 ft^3. However, the actual volume occupied by the accumulating TVS also is probably is significantly higher due to moisture content, which is unknown. Thus, it is not possible to estimate the actual rate of loss of digester operating volume due to the accumulation of TVS. However, the following caveat with respect to the rate of accumulation of TVS is necessary. However, the rate of TVS accumulation probably is being mitigated to a degree by the accompanying increase in SRT. Because the ultimate biodegradability of these accumulating TVS is essentially 100 percent, the fraction of the accumulating TVS remaining should decrease with time as further microbial degradation occurs. Therefore, the accumulation rate of 732 lb per year represents an average value for the 12 months of data collection and the rate at the beginning of this 12-month period probably was higher and probably was lower at the end of this period.

Although the available data preclude anything more than a speculative estimate of the rate loss of the CP digester operating volume, it is clear that a decrease in operating volume is occurring with time due to the accumulation of FS and TVS as the result of settling. As mentioned earlier, this accumulation of FS and TVS is increasing the SRT in the digester. Consequently, the HRT is decreasing and eventually will be reduced to below the critical value for process stability. Therefore, the degree of influent stabilization eventually will approach zero. The data collected during the 12 months of this study do not provide any indication that HRT was reduced below the critical value for process stability. However, it appears reasonable to conclude that this critical HRT eventually will be reached and removal of the accumulated FS and TVS will be necessary before that point to maintain process stability.

As noted in Table 4-1, the density of the fecal coliform group of bacteria was reduced from 5.61 to 1.78 $\log_{10}$ colony-forming units per gram of manure during anaerobic digestion. This translates into a reduction in excess of 99.9 percent and suggests a significant reduction in the density of any pathogens possibly present.

Biogas Production and Characteristics

Biogas Production—As indicated above, the volume of biogas produced daily at CP during the period of data collection to assess process performance is unknown. Although the volume of biogas used to generate electricity was metered and recorded daily, the volume of biogas disposed of by flaring was not measured. Only a record of days when flare operation was observed was established. This record has little value because the number and duration of individual flaring events on days when flare operation was observed was not determined. In addition, it is probable that flare operation was not always observed due to time of day. For example, it is likely that flare operation during nighttime hours was not always observed since flare operation was automatically triggered when biogas pressure in the plastic collection dome exceeded a predetermined value. Thus, no basis exists for estimating total biogas production from the CP anaerobic digester, and it only can be concluded that total biogas production was somewhat greater than engine-generator set utilization.

As noted above, CP biogas utilization averaged 27, 370 ft^3 per day, which translates into 1,998 ft^3 per sow-year for 5,000 sows. This is comparable to the rate of 1,837 ft^3 per sow-year that was determined from the analysis of the performance of a covered anaerobic lagoon-biogas utilization system located in North Carolina (Martin, 2002) when the presence of 1,200 gilts at CP is considered.

Biogas Characteristics—The characteristics of the biogas produced by the CP anaerobic digester are summarized in Table 4-3. The percentages of methane and carbon dioxide were corrected to account for nominal contamination in the biogas samples as indicated by the presence minimal percentages of oxygen/argon and nitrogen. As indicated by the small standard deviations, there was little variation in the percentages of methane and carbon dioxide over the 12 months of data collection. This indicates that there was no inhibition of methanogenic activity due to the previously discussed variation in HRT.

Based on the average methane content of the CP biogas, it should have a higher heating value of 679 Btu per ft^3. The slightly lower mean higher heating value determined by calculation (Table 4-3) of 673.5 Btu per ft^3 reflects the nominal degree of sample contamination mentioned above. Based on the difference between the higher and lower heating values, it appears that the average moisture content of the CP biogas was approximately 92 gallons of water per 10,000 ft^3 of biogas produced. Therefore, daily digester effluent volume should have been approximately 250 gallons less than the influent volume. This is a reduction of less than two percent in the assumed average daily influent volume of 13,846 gallons per day and suggests that is reasonable to consider daily digester influent and effluent volumes to be equal. Not doing so would ignore the probability that sources of error of equal or greater magnitude, such as the determination of daily digester influent volume, did not exist in the daily determination of digester influent volume.

As also shown in Table 4-3, average sulfur content of CP biogas was 0.58 percent but with a substantial degree of variation among the samples analyzed. Of the total sulfur present, 99.99 percent or more was present as hydrogen sulfide. Other forms of sulfur present in some but not all samples included methanethiol, ethanethiol, i-propanethiol, n-propanethiol, s-butanethiol, t-butanethiol, carbon disulfide, and dimethyl sulfur. None of these compounds ever was detected in concentrations greater than three µL per L. The total sulfur concentration of 5,786 µL per L translates into an average biogas sulfur content of 0.556 lb of sulfur per 1,000 ft^3.

Biogas Utilization

During the 12 months of data collection, 9,331,400 ft^3 of biogas produced by the CP digester was utilized to generate 342,414 kWh of electricity with an online efficiency of 90.5 percent. However, the 12-month period of data collection included 32 days when the engine-generator set was out of service or only was partially in service due to various mechanical and electrical problems. These problems involved both the engine and the generator and included engine valve failure on two occasions.

For the 333 days that the engine-generator set was fully in service, 27,370±8,117 ft^3 of biogas was utilized to generate 997±262 kWh of electricity per day. The on-line efficiency of the engine-generator set during these 333 days was 94.8 percent, which exceeds that of a typical coal-fired electrical generating station, and 36.4 ± 9.8 kWh were generated per 1,000 ft^3 of biogas utilized. Based on the lower heating value of 661.8 Btu per ft^3 (Table 4-3), the average thermal efficiency of the conversion of biogas heat energy to electrical energy of the engine-generator set was approximately 22 percent. This low conversion efficiency is probably the result of the utilization, on average, of only approximately 52 percent of the engine-generator set's rated capacity of 80 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).

If the engine-generator set mechanical and electrical problems mentioned above have not occurred, it appears reasonable to estimate that 9,990,050 ft^3 of biogas would have been utilized to generate 363,905 kWh of electricity during the 12 months of data collection to assess system performance. This estimate is based on the assumption of an on-line efficiency of 94.8 percent and an average directly connected load demand of 997 kWh per day.

As indicated earlier, biogas utilization at CP during the study was limited to generating electricity necessary to satisfy a directly connected load. This arrangement was necessary because SCP would not purchase any electricity generated by CP and constrained the potential for using biogas to generate electricity for several reasons. As mentioned above, the average fraction of the engine-generator set's rated capacity utilized was only 52 percent, but there was substantial day-to-day variability. For the 333 days that the engine-generator set was fully in service, the daily average directly connected demand was 41.6±9.1 kW. This degree of day-to-day variability in the directly connected load in combination with the probable intra-day variability suggests that flare operation could have been primarily in response to the variability in the directly connected electrical demand. Because the coefficient of variation for biogas utilization, 30 percent, was similar to the coefficient of variation in demand, 22 percent, it seems reasonable, by extension, to conclude that biogas production was relatively constant. In addition, it also seems reasonable to conclude that CP has the ability to generate at least 1,200 kWh of electricity per day. This would increase utilization of generator capacity and increase the efficiency of conversion of biogas heat energy to electricity.

Gaseous Emissions

Methane—As indicated earlier, it appears that CP has the ability under current operating conditions to utilize at least 9,990,050 ft^3 of biogas annually to generate electricity to satisfy onsite demand. This translates into the capture and oxidation of at least 6,783,244 ft^3 of methane annually without consideration of the unknown volume of biogas disposed of by flaring. Because methane has 21 times the heat trapping capacity of carbon dioxide (U.S. Environmental Protection Agency, 2002), the reduction in methane emissions being realized is equal to a reduction in the emission of an equivalent of 3,022 tons of carbon dioxide per year or 1,209 lb per sow-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 144 tons per year. Therefore, the net reduction in methane emissions, on a carbon dioxide equivalent basis, is 2,878 tons per year or 1,151 lb per sow-year. This estimate is based on the reasonable assumption that methane emitted from a conventional anaerobic lagoon designed for the same number of animals will be equal to the methane produced in the CP digester.

However, the reduction in greenhouse gas emissions due to biogas production and utilization at CP 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 363,905 kWh of electricity that could be generated annually by CP using biogas potentially reduces fossil fuel derived carbon dioxide emissions by an additional 409 tons per year or 164 lb per sow-year.

Therefore, the potential total reduction in greenhouse gas emissions under current operating conditions, on a carbon dioxide equivalent basis, is estimated to be at least 3,287 tons per year or 1,315 lb per sow-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.

Hydrogen Sulfide—As mentioned earlier, the sulfur content of CP biogas is 0.556 lb per 1,000 ft^3, and essentially all of the sulfur present is as hydrogen sulfide. Assuming again that the potential for biogas utilization at CP is 9,990,056 ft^3 annually, a reduction in hydrogen sulfide emissions of at least 5,902 lb per year or approximately 1.2 lb per sow-year is being realized. Although some of this reduction in hydrogen sulfide emissions is due to oxidation of sulfuric acid, which is captured in the engine oil, oxides of sulfur (SO_x) also are being formed and emitted to the atmosphere in the engine-generator set exhaust as well as during flaring. Because the fraction of biogas hydrogen sulfide that is being oxidized to sulfuric acid is not known, an estimate of SO_x emissions resulting from biogas combustion is not possible.

Odors—As stated earlier, the need to reduce odors was one of the catalysts for constructing an anaerobic digestion and biogas utilization system at CP. Walker (2001) reported that odor threshold determinations on seven occasions from 22 May 2000 through 6 June 2001 in the immediate vicinity of the digester were all below the compliance level of 6,000 established by the state of Colorado but ranged from 658 to 5,662. The seven-sample mean was 2,842. Thus, it appears that the objective of odor control in the immediate vicinity of the digester is being realized.

Effluent Disposal

As described earlier, the effluent from the CP anaerobic digester is discharged to an earthen storage structure, which was designed as an evaporation pond. Mattocks *et al.* (2002) reported that the elevation of the liquid surface in the storage structure was approximately 271.5 feet at the beginning of the study and approximately 270 feet 12 months later at the end of the study. This indicates that the evaporative loss over the 12-month study period was somewhat in excess of precipitation plus the estimated 5,073,790 gallons (675,692 ft^3) of digester effluent discharged to storage structure. The stage-storage capacity table for the storage structure prepared by the engineering firm that designed the storage structure, Agricultural Engineering Associates, indicates that the liquid surface area at the elevation of 271 feet is 47,585 ft^2. Therefore, the calculated rate of evaporation for the 12-month study period is in excess of 14 feet per year. This is substantially higher than the average free water evaporation rate minus average precipitation for southeastern Colorado of approximately 3.7 feet per year. If, however, the actual average elevation of the liquid surface was 272 feet, the liquid surface area in the storage structure increases to 237,708 ft^2. This would reduce the rate of evaporation to a more reasonable value of somewhat in excess of 2.8 feet per year and explain the 1.5 feet reduction in the elevation of the liquid surface in the storage structure over the 12-month study period.

Because the samples of the storage structure contents were grab samples taken 12 inches below the liquid surface and did not provide representative samples of the contents of the storage structure, construction of materials balances to determine the fate of various constituents in the digester effluent discharged into the pond were not possible.

It appears reasonable, however, to expect that the concentrations TS, VS, FS, COD, ON, TP, Cu, and Zn in the storage and evaporation pond to be substantially higher than those in the digester effluent given the previously discussed magnitude of evaporative loss. As indicated in Table 4-4, the mean concentrations of TS, TVS, FS, COD, and ON in the contents of the storage and evaporation pond were higher than those in the digester effluent by magnitudes that are statistically significant ($P<0.01$). However, the increase in the concentration of FS was less than expected and there were no statistically significant differences in the concentrations of TP, Cu, Zn, or S. This finding is consistent with the expectation that a substantial degree of settling of particulate matter is occurring in the storage and evaporation pond and these elements are being concentrated in the accumulating particulate matter. This concentration of TP and S could be viewed as beneficial with respect to the value of the accumulating solids as a concentrated source of these nutrients. S is an important plant micronutrient, and the addition of S to alkaline soils can be beneficial in reducing soil pH. However, the concurrent concentration of copper and zinc raises concerns about phytotoxicity and bioaccumulation in crops raised for animal and human and consumption. Thus, the benefits of effluent disposal by evaporation may be offset by the possible difficulty in the eventual ultimate disposal of the particulate matter accumulating in the storage and evaporation pond.

The statistically significant ($P<0.01$) increases in the concentrations of TKN and ON and the decrease in the concentration of NH_4-N (Table 4-4) suggest that loss of NH_3 by volatilization from the storage and evaporation pond is substantial and probably approaches the mass in the digester effluent discharged to the pond annually. However, the rate of NH_3 volatilization cannot be quantified because the necessary nitrogen balances cannot be constructed from the available data.

The reason or reasons for the statistically significant increases ($P<0.01$) in the concentrations of BOD_5 and VA (Table 4-4) are unclear. However, the increase in the concentration of BOD_5 simply may be a reflection of the microbial degradation of more complex organic compounds to less complex compounds in the storage and evaporation pond. The BOD_5 determination only captures those compounds that can be readily oxidized microbially to carbon dioxide and water within 5 days and does not include those more complex compounds that are less readily but ultimately biodegradable. The degradation of more complex and therefore less readily biodegradable organic compounds in the storage and evaporation pond appears to be also responsible for the increase in the concentration of VA. Although a seasonable increase in VA concentration in the storage and evaporation pond would be expected as temperature and the activity of methanogenic bacteria decreases, VA concentrations increased through the summer and into the early fall and then decreased in the winter. There appears to be no logical explanation for this pattern of change in VA concentrations in the contents of the storage and evaporation pond.

Walker (2001) also reported that the average of odor threshold determinations on eight occasions from 22 May 2000 through 28 June 2001 in the immediate vicinity of the digester effluent storage and evaporation pond was below the compliance level of 6,000 established by the state of Colorado. However, odor threshold levels ranged from 516 when the pond surface was frozen to 15,222 in early June 2001. The compliance level of 6,000 also was exceeded in late May 2000 and in early April 2001. This pattern of odor threshold violation is somewhat consistent with the increase in storage and evaporation pond VA concentrations described above. It probably is the result of increased microbial activity in the settled particulate matter as temperature of this material increases.

The absence of any statistically significant difference between the digester effluent and the storage and evaporation pond samples in the densities of fecal coliforms (Table 4-4) suggests no regrowth of fecal coliforms and presumably pathogens in the storage and evaporation pond.

Economic Analysis

Introduction—The 12 months of data collection for the evaluation of the anaerobic digestion and biogas utilization system at CP appears to have had the determination of impact on farm energy costs as an objective. However, much of the information necessary for a detailed cost analysis of the system to determine economic viability was not obtained. For example, there is no record of the annual kWh use or cost prior to biogas production and utilization at CP because swine production started with the anaerobic digestion-biogas utilization system in place. Therefore, a number of assumptions were necessary in the preparation of the economic analysis presented below and the results of the analysis should be considered in that context.

Capital Cost—Moser and Mattocks (2000) reported the total capital cost of the CP anaerobic digester and biogas utilization system to be $368,000. As shown in Table 4-5, this sum includes the cost of the influent collection and mixing tank and the pump for mixing and the electrical intertie, which is not being used. It does not include the cost of the effluent storage and evaporation pond, which would be required without digestion. Based on the 5,000-sow capacity of CP, the cost per sow of the system is a relatively modest $73.60 per sow.

Value of Electricity Generated—As discussed earlier, the biogas produced over the 12-month study of data collection to characterize the performance of the CP anaerobic digestion-biogas utilization system was used to generate 342,414 kWh of electricity, which was used onsite. Because CP never operated without the use of biogas to generate electricity, the monetary value of the electricity generated and used onsite could not be determined directly from the difference between pre and post anaerobic digestion electricity costs. In addition, simply estimating the value of the electricity generated by and used onsite based on the current cost per kWh incurred by CP, $0.04 per kWh based on results of a recent farm energy audit, would not reflect any reduction on demand charges.

However, the results of an energy audit of another 5,000 -sow farrow-to-wean swine operation in southeastern Colorado were available to estimate the combined energy and demand cost per kWh of electricity that CP would pay without anaerobic digestion and biogas utilization. The results of that energy audit indicate that CP would be paying $0.0669 per kWh. Based on that unit cost, the electricity generated during the 12-month period of this study has an estimated value of $22,907. However, the previously discussed engine-generator set mechanical and electrical problems with the loss of 32 days of biogas utilization resulted in an atypically low on-line efficiency of 90.5 percent. Thus, it seems reasonable to use the on-line efficiency value of 94.8 percent for the 333 days of engine-generator set operation that required only normal repairs and maintenance to estimate the value of the electricity that should be generated annually. At an on-line efficiency of 94.8 percent, 363,905 kWh of electricity would be generated annually and provide a gross return of $24,345 per year.

The revenue derived from anaerobic digestion with biogas utilization is not limited, however, to the value of the electricity generated and used onsite. The cost of electricity purchased from SCP also is reduced from the previously noted $0.0669 to $0.04 per kWh due to the apparent elimination of demand charges. Based on the results of this study and the CP energy audit, the use of biogas to generate electricity potentially reduces the purchase of electricity from SCP from 921,950 to 554,600 kWh per year. Therefore, it is estimated that CP is saving an additional $14,919 per year due to the rate reduction from $0.0669 to $0.04 per kWh for electricity purchased from SCP. Thus, the total reduction in the cost of electricity used by CP, which represents the gross revenue realized by anaerobic digestion and biogas utilization, is estimated to be $39,264 per year.

Previously, Mattocks *et al*. (2001) estimated the value of the electricity generated at CP from biogas to be $84,000 per year based on the difference between the average monthly cost of electricity purchased by CP and that for other operations of comparable size. This estimate was based on anecdotal information and appears to not have considered possible differences in the efficiency of electricity utilization. The results of the energy audit of CP mentioned earlier indicated that the overall efficiency of energy use at CP is very high as compared to similar operations.

<u>Annual Costs</u>—Mattocks et al. (2001) reported that operation of the CP anaerobic digester and engine-generator set required less than 45 minutes per day of semi-skilled labor. Assuming a labor cost including fringe benefits of $15 per hour, the annual labor cost for operation of the CP engine-generator set can be estimated to be $4,106 per year. However, this estimate does not include the cost of replacement parts, lubricants, etc. and no record of these costs could be obtained. Also, not included is the cost of replacing the digester plastic biogas collection dome after normal deterioration or removal of accumulated solids from the digester. The plastic biogas collection dome has an estimated life of 10 years.

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 CP system under current operating conditions would be $5,459 per year, which is approximately 1.5 percent of the capital cost of the system. Given the $4,106 estimate for annual labor cost, a total annual cost of $5,459 per year allows $1,353 per year for replacement parts, lubricants, etc. This sum may not be adequate over an estimated system life of 20 years when the costs of periodic engine rebuilding that is necessary, especially with biogas used as a fuel, and biogas collection dome replacement are considered. However, the lack of long-term operating experience with this system precludes assuming a higher annual operating and maintenance cost that can be justified.

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 CP anaerobic digestion-biogas utilization system from onsite use of the electricity generated, as discussed above, is estimated to be $39,264 at a cost for operation and maintenance of $5,459 per year. Thus, net revenue generated is $33,805 per year and 10.9 years will be required to recover the capital invested, $368,000, if the time value of money is not considered.

At an interest rate of seven percent over 20 years for borrowed capital, the annual cost of the capital invested in the CP anaerobic digestion system is $34,736 per year. Therefore, the net revenue being produced by the generation and onsite use of electricity from biogas at CP is negative and is estimated to be reducing net farm income by about $931 per year or $0.19 per unit of sow capacity per year. Therefore, the rate of return with internal financing, which was the method of financing the CP system, is slightly less than seven percent.

Given the relatively low cost of electricity purchased by CP, these findings are not surprising and illustrates the sensitivity of the economics of anaerobic digestion of animal manures with biogas utilization to generate electricity to local electric rates. If SCP rate was $0.04 per kWh higher, the CP system would add $13,625 ($2.72 per unit of sow capacity) per year after debt service to net farm income.

In considering the results of this economic analysis of the CP anaerobic digestion-biogas utilization system, the following should be recognized. Unlike other alternatives for swine waste stabilization to control odors and reduce greenhouse gas emissions and water pollution potential, such as aeration, this approach produces a usable form of energy and revenue to at least partially offset system cost. In addition, there are several possible approaches to increase the revenue realized. One is the interconnection with SCP, which was accomplished after this study ended. This will allow revenue to be generated from essentially all of the biogas produced with flaring required only when the engine-generator set is out of service for maintenance or repairs. Interconnection also may increase the thermal efficiency of the conversion of biogas to electricity by allowing the rated capacity of the engine-generator set to be more fully utilized. Unfortunately, the additional revenue realized cannot be estimated at this time due to the lack of knowledge of total biogas production.

Replacing the 80 kW engine-generator set with a smaller unit that would operate at or near maximum capacity also would increase the gross revenue derived from generating electricity. As discussed earlier, only an average of 52 percent of the CP engine-generator set rated capacity was being utilized during this 12-month study. This reduced the thermal conversion efficiency of biogas to electricity from a possible 30 to 22 percent. However, a more rigorous analysis of this option would be necessary to determine if the required capital investment can be justified.

The recovery and utilization of waste heat from the engine-generator set for domestic hot water or space heating or both is another possible option to generate additional revenue. Engine-generator set heat losses via engine coolant and exhaust gases constitute approximately 28 and 33 percent, respectively, of biogas energy content (Koelsch and Walker, 1981). Given that heat recovered from the engine coolant is used to heat the CP digester, it is probable that little additional heat could be recovered for other uses especially in winter months. However, a preliminary calculation indicates that 2.17×10^9 Btu of heat in exhaust gases is lost from the CP engine-generator set annually. The results of the CP energy audit indicate that CP uses 675×10^3 ft^3 (675 Mcf) of natural gas annually at a cost of $4.50 per Mcf for water heating. Assuming 31 percent of the exhaust gas waste heat could be recovered for water heating, a gross return of $3,037 would be realized in avoided natural gas cost. Again, this option would have to be analyzed more rigorously to see if the required capital investment is justified.

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Table 3-1. Physical, chemical, and microbiological parameters used to characterize the Colorado Pork anaerobic digester influent, effluent, and storage structure samples.

Parameter	Analytical method
Moisture	AOAC* 925.10, 930.15
Total volatile solids	EPA† 160.4
Total settleable solids	EPA 160.5
Biochemical oxygen demand, 5-day	Standard Methods# 5210B
Chemical oxygen demand	ASTM§ D 1252-88
Volatile acids	Standard Methods 5560C
Alkalinity	Standard Methods 2320B
Ammonia nitrogen	AOAC 920.03
pH	EPA 150.1
Nitrogen	AOAC 970.02
Phosphorus	ICP-AOAC 985.01, 953.01
Potassium	ICP-AOAC 985.01, 953.01
Sulfur	ICP-AOAC 985.01, 953.01
Magnesium	ICP-AOAC 985.01, 953.01
Calcium	ICP-AOAC 985.01, 953.01
Sodium	ICP-AOAC 985.01, 953.01

Table 3-1. Continued.

Parameter	Analytical method
Iron	ICP-AOAC 985.01, 953.01
Aluminum	ICP-AOAC 985.01, 953.01
Manganese	ICP-AOAC 985.01, 953.01
Copper	ICP-AOAC 985.01, 953.01
Zinc	ICP-AOAC 985.01, 953.01
Fecal coliforms	Standard Methods 9221E

[*] Association of Official Analytical Chemists, Washington, DC.

[†] U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Cincinnati, Ohio.

[#] Standard Methods for the Examination of Waste and Wastewater, American Public Health Association, Washington, DC.

[§] ASTM International, West Conshohocken, Pennsylvania.

Table 3-2. Parameters and methods used to characterize the composition of Colorado Pork biogas.

Parameter	Analytical method
Hydrogen	ASTM D 1945
Oxygen/argon	ASTM D 1945
Nitrogen	ASTM D 1945
Carbon dioxide	ASTM D 1945
Methane	ASTM D 1945
Ethane	ASTM D 1945
Propane	ASTM D 1945
Isobutane	ASTM D 1945
N-butane	ASTM D 1945
Isopentane	ASTM D 1945
N-pentane	ASTM D 1945
Hexanes+	ASTM D 1945
High heating value	Calculated
Low heating value	Calculated
Hydrogen sulfide	ASTM D 5504-94
Other sulfur compounds	ASTM D 5504-94

Table 4-1. Comparison of the Colorado Pork anaerobic digester mean influent and effluent concentrations for the period 24 April 2000 through 3 April 2001[*].

Parameter	Digester influent	Digester effluent	Reduction, %
Total solids, mg/L	47,181[a]±19,804	21,161[b]±4,049	55.1
Total volatile solids, mg/L	30,858[a]±13,652	11,114[b]±1,956	64.0
Fixed solids, mg/L	16,460[a]±8,394	10,111[b]±2,753	38.6
Biochemical oxygen demand, 5-day, mg/L	24,620[a]±10,114	4,459[b]±1,831	81.9
Chemical oxygen demand, mg/L	61,404[a]±21,576	19,920[b]±3,714	67.6
Volatile acids, mg/L	7,055[a]±2,033	599[b]±331	91.5
Total Kjeldahl nitrogen, mg/L	4,504[a]±758	4,276[a]±448	nsd
Ammonia nitrogen, mg/L	3,244[a]±509	3,423[a]±421	nsd
Organic nitrogen, mg/L	1,260[a]±408	853[b]±164	32.3
Total phosphorus, mg/L	1,002[a]±441	526[a]±169	47.5
Copper, mg/L	11[a]±5	7[b]±2	36.3
Zinc, mg/L	95[a]±38	56[b]±16	41.0

Table 4-1. Continued.

Parameter	Digester influent	Digester effluent	Reduction, %
Sulfur, mg/L	579[a]±140	363[b]±68	37.3
Fecal coliforms, log_{10} CFU/g[†]	5.61[a]±0.41	1.78[b]±1.24	99.9+
pH	8.0[Å]±0.3	8.4[b]±0.2	n/a

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

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

Table 4-2. Colorado Pork anaerobic digester mass reductions.

Parameter	Reduction, lb/day
Total solids	3,007
Total volatile solids	2,281
Fixed solids	726
Biochemical oxygen demand, 5-day	2,329
Chemical oxygen demand	4,794
Volatile acids	746
Total phosphorus	55
Copper	0.46
Zinc	4.51
Sulfur	24.9

Table 4-3. Colorado Pork biogas characteristics.

Parameter	Mean ± standard deviation
Methane, %	67.90±1.79
Carbon dioxide, %	32.10±1.79
Higher heating value, Btu/ft^3	673.5±17.9
Lower heating value, Btu/ft^3	661.8±17.6
Total sulfur, µL/L (ppm)	5,786.0±1,243.5

Table 4-4. Comparison of the characteristics of the digester effluent and storage and evaporation pond contents[*].

Parameter	Digester effluent	Storage and evaporation pond contents
Total solids, mg/L	21,161[a]±4,049	32,775[b]±9,670
Total volatile solids, mg/L	11,114[a]±1,956	17,697[b]±6,661
Fixed solids, mg/L	10,111[a]±14,874	14,874[b]±3,570
Biochemical oxygen demand, 5-day, mg/L	4,459 [a]±1,831	17,001 [b]±6,887
Chemical oxygen demand, mg/L	19,920 [a]±3,714	42,102 [b]±10,640
Volatile acids, mg/L	599[a]±331	6,984[b]±2,584
Total nitrogen, mg/L	4,276[a]±448	3,708[b]±332
Ammonia nitrogen, mg/L	3,423 [a]±421	2,639 [b]±379
Organic nitrogen, mg/L	853[a]±164	1,069 [b]±256
Total phosphorus, mg/L	526[a]±169	593[a]±120
Copper, mg/L	7[a]±2	8[a]±2
Zinc, mg/L	56[a]±16	57[a]±16
Sulfur, mg/L	363[a]±68	317[a]±79
Fecal coliforms, $\log_{10}$ CFU/g[†]	1.78[a]±1.24	1.87[a]±0.95

Table 4-4. Continued.

pH	8.4^{a}±0.2	8.4^{a}±0.2

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

† Log_{10} colony-forming units per g.

Table 4-5. Cost of the Colorado Pork anaerobic digestion and biogas utilization system (Moser and Mattocks, 2000).

Item	Cost
Soil testing and earthwork	$13,900
Digester and equipment*	$191,200
Engine-generator set†	$67,000
Electrical and intertie	$17,600
Structure for engine-generator set, piping, etc.	$35,400
Engineering	$38,900
Start-up	$4,000
Total	$368,000

*Includes influent collection and mixing tank and pump for mixing.

†Reconditioned unit.