On-Farm Biogas Production and Utilization for South Carolina Livestock and Poultry Operations

PROJECT SUMMARY

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The overall goal of this project was to determine which type of anaerobic digester has the greatest potential for implementation on South Carolina livestock and poultry farms. The factors that were considered were the complexity of operation, net energy available for use, construction costs, and the cost to produce biogas energy.

The most common types of anaerobic digesters that have been used to treat animal manure and to produce biogas on-farm are the mixed tank, plug flow, and covered lagoon digester. A detailed literature review of the performance and operating characteristics of anaerobic digesters was conducted. Data was reviewed relating to the following factors that influence digester performance: temperature, loading rate, ammonia toxicity, mixing, biogas production from intermittently mixed reactors operated at low temperatures, and biogas production from covered lagoon digesters (CLD).

Performance of Mesophilic Anaerobic Digesters

The available models for the prediction of methane production from animal manure were reviewed. The model presented by Hill (1991) (equation 4) provided the best predictions of mesophilic biogas energy production from animal manure under ideal steady-state conditions (well-mixed, T=95°F). Volumetric methane productivity predictions, L CH_4/L – day, using Hill’s model correlated very well with data from swine, dairy, beef, and poultry manure digesters. The correlation coefficient, R, was 0.962.

The amount of biogas that can be generated from swine, dairy, beef, and poultry manure using a mesophilic reactor was calculated using Hill’s model (Table 1).

Table 1. Digester volume and energy production for on-farm biogas digesters maintained at a temperature of 95 °F (35 C).

Manure Type	VS_{IN} g VS/L	HRT days	σ_s [a] g VS/L-day	Φ_{MAX} [b] L CH_4/L-day	DV [c] ft^3/AU_{lb}	ft^3 CH_4 / AU_{lb}-day [d]	Btu / AU_{lb}-day [e]
Swine: Feeder-to-Finish							
Slurry, 5 % TS	38.7	15	2.58	0.825	52.8	43.6	39,900
Pit-Recharge, 2.7% TS	20.1	15	1.34	0.430	101.7	43.7	40,000
Flush, 1 % TS	7.7	15	0.51	0.164	264.3	43.3	39,700
					Average =	43.5	39,800
Swine: Farrow-to-Wean							
Slurry, 5 % TS	38.1	15	2.54	0.812	28.4	23.1	21,200
Pit-Recharge, 1.5% TS	11.4	15	0.76	0.244	94.5	23.1	21,200
Flush, 0.5 % TS	3.8	15	0.25	0.080	283.5	22.7	20,800
					Average =	23.0	21,000
Dairy							
Slurry, 8.2 % TS	68.1	20	3.41	0.401	56.0	22.5	20,600
Flush, 1.78 % TS	14.7	20	0.74	0.087	260.0	22.6	20,700
					Average =	22.5	20,600
Beef							
Slurry, 12 % TS	101.9	15	6.79	1.634	17.0	27.8	25,500
Flush, 2 % TS	16.9	15	1.13	0.278	102.2	28.4	26,000
					Average =	28.1	25,700
Poultry: Layer							
Slurry, 14 % TS	105.1	50	2.10	0.666	91.5	60.9	55,800
Flush, 2 % TS	15.0	22	0.68	0.217	282.0	61.2	56,100
					Average =	61.1	56,000

[a] To convert loading rate from g VS/L-day to lb VS/ft^3-day multiply by 0.0624.
[b] Volumetric methane productivity calculated using equation 4.
[c] DV = digester volume per 1,000 lb live weight. See Table 6 for volumes.
[d] ft^3 CH_4/AU_{lb}-day = Φ_{MAX} x DV x 0.99986
[e] Btu/AU_{lb}-day = ft^3 CH_4/AU_{lb}-day x 916 Btu/ft^3 CH_4.

Estimates were also made of the amount of biogas energy that would be required to maintain the reactor temperature at 95° F during the winter. The results indicated the following.

- Large dilution volumes associated with liquid manure handling systems make it impossible to achieve loading rates in the most desirable range due to limitations on the minimum hydraulic retention time.
- The most desirable loading rates for all species are obtained with slurry manure handling systems.
- The low loading rates common to liquid manure handling systems results in a decrease in volumetric methane productivity and must be compensated for by a larger digester volume. Therefore, the volumetric methane productivity is a measure of how well the reactor vessel is utilized.
- The amount of methane produced per animal unit was the same for all loading rates. The primary factor that influences the amount of biogas generated per animal unit (1,000 lb live weight) per day is the amount of volatile solids produced per animal unit per day.
- Construction of the reactor vessel is the single largest initial cost of a mesophilic anaerobic digester. Using large amounts of water to remove manure from animal facilities (flush and pit-recharge systems) increased the size of the anaerobic digester and the cost of the reactor by 2 to 10 times that of the equivalent slurry system.

- The energy required to heat the influent manure dominates the energy requirement for digester heating, and limits the amount of biogas energy that is available for use. Insulation of the reactor vessel is helpful but is not the limiting factor in the use of mesophilic digestion to produce energy on-farm during the winter.
- Liquid manure handling systems add large volumes of water that must be heated without increasing the amount of energy that can be produced. Therefore, the amount of energy needed to heat the digester to 95° F is often greater than the energy produced by mesophilic digestion. As a result, the digester temperature will fall to a less than ideal equilibrium temperature and no biogas energy will be available other uses.
- Farrow-to-wean swine farms require a significant amount of energy for space and water heating during the winter. However, only 3% of the biogas energy produced would be available for space or water heating when it is needed most.
- Thirty-three percent of the biogas energy produced on a feeder-to-finish swine farm would be available during winter if a pit-recharge manure handling system is used. Potential uses of the energy would be space heating for the farm office, water heating for the farm and residence, or electrical generation.
- If the objective of the digester installation is to produce as much available energy as possible year-round manure must be handled as slurry with minimal addition of water.
- A slurry manure digester on an egg producing poultry farm appears to have the greatest potential for on-farm biogas production during the winter followed by dairy. However, implementation of anaerobic digestion is difficult on poultry farms.

Even though South Carolina has a mild winter, the large amounts of dilution in liquid swine and dairy manure makes a heated digester operated at steady-state conditions impractical. Swine and dairy producers would need to implement manure handling techniques that minimize the use of water to use a conventional heated digester. This is very unlikely since such manure handling systems require more labor and tend to cause more odor. The simple construction of the covered lagoon digester, and its ability to provide biogas during the winter months rendered it the only practical on-farm digester option for swine and dairy farms that use liquid manure handling systems.

Development of a New Covered Lagoon Digester Model

When this project was initiated it was believed that the currently available methods of predicting digester performance were adequate. However, neither Hill's model as presented nor the *FarmWare* software provided by the *AgStar* project (EPAb, 1995) was sufficient to describe all of the required operational characteristics of a covered lagoon digester. Comparison of the *FarmWare* biogas production predictions for a covered lagoon digester (CLD) with data from a new CLD indicated that the model over-predicted biogas production by 178% on the average. None of the available models described the operational characteristics of a covered lagoon digester or any type of digester that operates at less than optimal temperature and under non-steady loading conditions. In particular the factors that must be considered are the effects of unsteady volatile solids loading rate, sludge build-up, temperature, and mixing.

None of the literature concerning covered lagoon digesters addressed the sludge issue. Lagoon design methods (ASAE EP403.2, 1998), and experience, indicate that sludge build-up can be significant and must be taken into consideration.

The covered lagoon digester is relatively simple to construct, but the operational characteristics are complicated. A new model was developed based on the literature, and data taken as a part of this project, to provide a more complete description and understanding of the operational characteristics and biogas production of a CLD. Swine and dairy farms were considered the most likely to implement CLD technology. Therefore, model development focused on applications for swine and dairy farms.

Relationships were developed either from data available in the literature, or data taken on South Carolina swine and dairy farms, to quantify the following input and operating variables:

- CLD temperature,
- total (TS) and volatile solids (VS) content of swine and dairy manure,
- effects of temperature and mixing on the fraction of VS destroyed,
- variation of VS degradability with solids retention time,
- variation in loading rate,
- sludge accumulation rate, and
- the amount of TS and VS that can be removed prior to a CLD using liquid-solid separation techniques.

The model output described the following operational characteristics of a covered lagoon digester:

- variation of biogas production with temperature and sludge removal operations,
- variation of loading rate with the active digester volume,
- variation in the hydraulic retention time,
- effect of sludge build-up on biogas energy production,
- variation in the removal of TS and VS, and
- effect of design loading rate on the maximum allowable solids retention time.

Model Results

The most significant model results are listed below.

- The amount of biogas produced rises and falls with the average ambient temperature.
- Sludge removal disrupts biogas production due to VS wastage.
- The CLD accumulates volatile solids that settle during the winter until spring. As temperatures warm in the spring the digestion rate increases and a large portion of the VS stored during the winter are destroyed.
- The loading rate of a CLD is not constant. During the first 6 weeks of operation the loading rate rapidly increased to 2.5 times the initial design value. During the winter the storage of VS and the loss of active digester volume due to sludge accumulation can cause the loading rate to increase by a factor of 5.
- Removal of sludge returns active volume and removes a large fraction of the retained VS. The loading rate returns to a value that is slightly higher than the initial design value.
- The CLD begins to fail when the ratio of the active digester volume to the design digester volume is 0.3. However, biogas production continues in a normal manner until the maximum loading rate, as defined by ammonia toxicity, is reached. Once the maximum loading rate is exceeded failure is sudden. Therefore, management of the sludge volume is critical to the operation of a CLD.
- The percentage of volatile and total solids removed from swine manure varied with ambient temperature. Removal of a large fraction of VS is critical to obtain odor control for the CLD effluent. The removal of VS ranged from 64% during the coldest weather to 98% when ambient temperatures reached 84 °F. On the average, 84% of the volatile solids were removed by the covered lagoon digester. Removal of VS includes the destruction of volatile solids and the storage of volatile solids by settling.
- The values for the mixing and design factor, F_M, range from 0.31 to 1.0. Reduction of F_M from a value of 0.65 to 0.31 reduced the biogas energy production of swine and dairy covered lagoon digesters by half. Since little information is available concerning the precise magnitude of F_M the

lower energy production values associated with poor mixing should be used to size boilers, engine-generator sets, or any other equipment intended to utilize biogas.

- Small loading rates can be used if it is desired to obtain large solid retention times (SRT). However, the large digester volume associated with small a SRT will greatly increase the construction costs of the CLD. The requirements for sludge management must be balanced against CLD construction cost. Designs that allow producers to remove sludge at 1 to 2 year intervals generally satisfy these requirements.

The computer model was used to simulate biogas energy production for a 3100 head feeder-to-finish swine facility (419 AU_{lb}) and a 370 cow (500 AU_{lb}) flush dairy facility. Manure treatment systems that include a covered lagoon digester with and without liquid-solid separation prior to the CLD were included for each case. The results indicated that:

- a CLD loaded at 10 lb VS/1,000 ft^3-day provides 3.5% more energy than a CLD loaded at 15 lb VS/1,000 ft^3-day,
- pretreatment of swine manure with a settling basin to reduce VS by 50% reduces energy production by 74%,
- pretreatment of dairy manure using a settling basin that reduces VS by 33% results in only a 20% reduction in biogas energy production,
- removal of the coarse VS from swine manure using a mechanical separator increases the degradability of the VS added to the CLD and slightly increases gas production (4%), and
- at a loading rate of 15 lb VS/1,000 ft^3 a swine CLD produces 7.2% more biogas on the average than a dairy CLD.

Comparison of the New CLD Model with Observations

Relatively little data were available in the literature concerning the operational characteristics and biogas production of a covered lagoon digester used to treat animal manure. In most cases, the authors reported the average daily biogas production from the CLD as the volume of biogas produced per unit area of cover per day (ft^3 biogas/ft^2 –day) or as the volume of biogas per unit CLD volume (ft^3 biogas/ft^3 –day). Anaerobic digestion of swine manure in a covered lagoon produced 0.02 to 3.02 ft^3 biogas/ft^2 –day or 0.03 to 0.15 ft^3 biogas/ft^3 –day. The model predicted that a CLD would produce 0.385 to 1.037 ft^3 biogas/ft^2 –day or 0.058 to 0.150 ft^3 biogas/ft^3 –day for swine manure. Therefore, model results lay within the range observed. The available data for treating dairy manure with a CLD indicated that the observed biogas production ranged from 0.23 to 1.1 ft^3 biogas/ft^2 –day or 0.03 to 0.23 ft^3 biogas/ft^3 –day. The model results for dairy manure were also within the observed range for both normalized measures of average daily production.

Very little monthly biogas production data could be found in the literature, and key variables such as the loading rate, sludge volume, or mean digester temperatures were lacking. Therefore, it was impossible to provide precise input data to the CLD model for comparison. However, one data set from a new CLD in North Carolina was used to compare monthly and annual average biogas production with model predictions.

A 20-ft deep CLD was used to treat manure from a 4,000 sow farrow-to-wean swine operation located in Johnston County, North Carolina. The CLD was partially covered and data was available for the first year of operation. The measured biogas production and the values predicted by the *AgStar* design program (EPAb, 1995), and the new CLD model are compared in Table 2.

Table 2. Comparison of the measured and predicted biogas production from a CLD in North Carolina used to treat manure from a 4,000 sow farrow-to-wean farm. (F_M = 0.31, F_C = 0.8)

		AgStar FarmWare Model		New CLD Model	
Month	Measured ft^3 Biogas/hr	Predicted ft^3 Biogas/hr	Error %	Predicted ft^3 Biogas/hr	Error %
January	450	1540	242	630	40
February	550	1850	236	594	8.0
March	650	2350	262	662	- 1.8
April	750	2500	233	1029	37
May	850	2620	208	1121	32
June	1100	2710	146	1143	3.9
July	1250	2770	122	1144	- 8.5
August	1200	2750	129	1123	- 6.4
September	1100	2670	143	1059	- 3.7
October	950	2510	164	935	- 1.6
November	850	2380	180	793	- 6.7
December	530	1840	247	586	11
ANNUAL	853	2374	178	902	5.7

The results indicated that:

- the *AgStar* model over predicted the biogas production by 122 to 247% with an average error of 178%,
- the percent difference between the data and the new CLD model ranged from - 8.5% to + 40% with an average error of 5.7%, and
- after the 5 month start-up period the average difference between the data and the predictions using the CLD model was -1.7%.

Comparison with the available data for average annual and monthly biogas production indicates that the new CLD model performs reasonably well. Additional work is needed to better define the mixing and design factor (F_M), and the collectable fraction of biogas (F_C). Better definition of the temperature factor, F_T, would also help to improve model reliability.

Covered Lagoon Digester Costs

One of the objectives of the project was to determine if anaerobic digestion technology could be cost-effective on South Carolina farms. The model results and information obtained from USDA -NRCS (Kintzer et al., 1998) on basin construction costs, and lagoon cover costs (Poly-Flex, 1998) were used to compare the construction costs of conventional lagoons, storage ponds, and four different manure systems that use a CLD. The results indicated that the cost of the basin liner was the major cost factor that influenced the cost of a conventional lagoon, storage or CLD. It was shown that a CLD system could be much smaller than a conventional lagoon if loading rates ranging from 10 to 15 lb VS/1,000 ft^3 - day are used. The higher the loading rate the smaller the CLD and the lower the cost.

The three lowest cost CLD systems for swine manure were:

- a CLD sized based on a loading rate of 15 lb VS/1,000 ft^3 - day,
- removal of 20% of the volatile solids using a mechanical separator and then treating the separator effluent with a CLD loaded at 15 lb VS/1,000 ft^3 - day, and

- removal of 52% of the volatile solids using a settling basin followed by a CLD loaded at 15 lb VS/1,000 ft^3 - day.

Using a settling basin to treat swine manure yielded the smallest CLD and had the lowest cost and eliminated sludge removal problems. However, biogas production fell by 74%. Therefore, it would be a poor option for energy production. Using a mechanical separator to treat swine waste prior to entering a CLD resulted in a CLD that was 20% smaller, required the removal of 30% less sludge, and yielded gas production that was slightly greater than a CLD without any type of liquid-solid separation.

Dairy manure is less degradable than swine manure. As a result, any type of anaerobic process provides less treatment than for swine manure. The best CLD system for a flush dairy used a gravity settling basin to remove the large solids followed by a CLD loaded at 15 lb VS/1,000 ft^3 - day. Removal of 33% of the VS from dairy manure only caused a 20% decrease in biogas energy production.

The CLD systems described above had construction costs that were less than a conventional lagoon that is lined with the same material (clay vs. synthetic liner). A storage pond used for swine manure will generally give off more odor than a lagoon, but is smaller and cheaper to build. Many of the CLD systems had construction costs that were similar or only slightly higher than the equivalent storage pond. These results indicate that it is possible to build a CLD manure treatment system that has similar costs as a conventional manure treatment system.

The cost to produce biogas energy was calculated based on the cost to own and maintain a CLD system for 15 years. The cost to produce biogas on-farm was expressed as the equivalent LP gas price. It was determined that the least expensive CLD systems could produce biogas energy at the same or lower cost than the purchase price of LP. Biogas can be generated on-farm at an equivalent LP price of $0.65 / gallon or less in many cases.

The analyses were performed for farms that ranged in size from 419 to 500 AU_{lb} (1 AU_{lb} = 1,000 lb live weight). This would be equivalent to the following swine farms: 3,100 head finishing farm, 968 sow farrow-to-wean farm, 13,967 head nursery farm, and a 296 sow farrow-to-finish farm. These represent the largest swine farms that can be built before the new South Carolina regulations for large swine facilities will apply. They also represent relatively small, but commercially viable farms. A 370-cow dairy or 500 AU_{lb} represents a commercially viable dairy that would consider using a flush system. Smaller dairies generally do not use flushing systems.

Uses of Biogas

Long-term, on-farm storage of biogas is not economical. Therefore, the gas needs to be used within a short time after being produced. The potential on-farm uses of biogas are: (1) direct burning for water heating, drying, or space heating, (2) fuel for an engine-generator set for production of electricity, and (3) absorption cooling of milk or other agricultural commodities (Roos, 1991).

A review of the literature indicated the following.

- The variation in biogas energy from month-to-month makes it difficult to use all of the energy.
- In general, the cost to produce electricity on-farm is greater than the purchase price of electricity from the utility or cooperative.
- A practical approach to biogas energy utilization is to select a few appliances or a boiler that can be used for heating applications and flare off the excess.
- Covered lagoon digester technology may be a good option for producers who need to expand, and have a lagoon that can be used as the holding pond.

Technology Transfer Activities

Two seminars were held in September 1998 for livestock producers, NRCS (Natural Resources Conservation Service) engineers, and staff from the SC Department of Health and Environmental Control (SCDHEC), and all others interested in alternative technologies for treating swine and dairy manure. The first meeting was held at Clemson University's Pee Dee Research and Education Center in Florence, SC. This location was selected because it is near the largest swine producing counties in South Carolina. The second meeting was held at the South Carolina Farm Bureau, in Columbia, SC. Columbia was selected to be convenient for SCDHEC employees, NRCS employees, and dairy producers.

The topics that were included in the seminar were:

- status of regulatory requirements for lagoon and storage pond liners, set backs, and special considerations given by the state regulatory agency to encourage the adoption of alternative technologies,
- definition and sizing of anaerobic treatment lagoons and storage ponds,
- operation and management considerations for covered lagoon digesters,
- sludge considerations for traditional lagoons and covered lagoon digesters,
- use of liquid-solid separation technologies to reduce sludge removal, and CLD size
- potential on-farm biogas energy production,
- comparison of the costs to construct conventional manure storages and CLD systems,
- cost to produce biogas energy on-farm, and
- potential uses of biogas.

Forty-three people attended the two meetings. Although the turnout was less than desired, the audience included key NRCS and SCDHEC personnel that would be involved in the adoption of CLD technology. In addition, several of the most progressive swine producers in the state attended. Also in attendance was the president of the South Carolina Pork Producers and a swine producer who is in charge of development for a major swine production company. The seminar was well received and served to generate interest in the possibilities of using CLD technology as a manure treatment option and an energy source.

Publications

Chastain, J.P., D.E. Linvill, and F.J. Wolak. 1999. *On-Farm Biogas Production and Utilization for South Carolina Livestock Operations.* Final report published by the Southeastern Biomass Energy Project, TVA, June 4, Muscle Shoals, Alabama, 129 pp.

Chastain, J.P. and D.E. Linvill. 1999. A Model of the Operating Characteristics of Covered Lagoon Digesters for Swine and Dairy Manure. Presented at the 1999 ASAE/CSAE-SCGR Annual International Meeting, Paper No. 994045. ASAE, 2950 Niles Rd., St. Joseph, MI 49085-9659.