Appendix A

Stoichiometry of the Anaerobic Digestion Process

Biogas from anaerobic digestion of sewage, food processing, animal and other wastes typically contains about 55% to 70% CH_4 and 30% to 45% CO_2. In some cases, much higher CH_4 content are reported, over 70% (see Chapter 2 of main report) and even up to 90% CH_4 in some cases. High methane content in biogas would be desirable, as it would reduce, in some cases even avoid, the need for CO_2 removal from the biogas, and direct utilization (after H_2S and moisture removal) as a vehicular fuels and other applications requiring compression. This Appendix briefly examines the potential for achieving high (>70%) methane content in the biogas as part of the anaerobic digestion process of dairy manures, to reduce or even avoid the need for a separate CO_2 removal operation.

Biogas production from organic substrates involves an internal redox reaction that converts organic molecules to CH_4 and CO_2, the proportion of these gases being dictated by the composition and biodegradability of the substrates, as already briefly discussed above. For the simplest case, the conversion of carbohydrates, such as sugars (e.g., glucose, $C_6H_{12}O_6$) and starch or cellulose ($C_nH_{n-2}O_{n-1}$), an equal amount of CH_4 and CO_4 is produced (50:50 ratio):

$$CnHn\text{-}2On\text{-}1 + nH_2O \rightarrow ½\ nCH_4 + ½nCO_2 \qquad (1)$$

In the case wastes containing proteins or fats, a larger amount of methane is produced, stoichiometrically from the complete degradation of the substrate. For proteins, the process is as follows:

$$C_{10}H_{20}O_6N_2 + 3H_20 \rightarrow 5.5\ CH_4 + 4.5\ CO_2 + 2NH_3 \qquad (2)$$

This yields a CH_4:CO_2 ratio of 55:45; the exact biogas composition will depend on the individual substrate protein.

For fats and vegetable oil (triglycerides), a typical CH_4:CO_2 ratio is 70:30:

$$C_{54}H_{106}O_6 + 28\ H_2O \rightarrow 40\ CH_4 + 17\ CO_2 \qquad (3)$$

These simplified examples can change according to effects from several factors:

- Reactions are often incomplete (typically up to half of the cellulose is refractory to microbial anaerobic degradation, and lignin is completely inert, for example).
- By-products are produced and voided in the digester effluent (e.g., acetic, propionic and other fatty acids and metabolites).
- Bacteria use these reactions to make more bacteria; thus, there is also some biomass produced as part of these metabolic processes.

The last two factors will reduce CH_4 somewhat more compared to CO_2 production, as the by-products and bacterial cells are generally more reduced than the substrates. However, these corrections are relatively minor, as most of the substrate degraded is indeed converted to CH_4 and CO_2 because bacterial biomass yields in anaerobic fermentations are quite low, typically less than 5% of the C in the substrate being converted to bacterial biomass (composition approximately $C_5H_8NO_2$). Incomplete digestion also does not affect gas composition significantly. For a first approximation, therefore, the three above factors can be disregarded for adjusting for expected CH_4:CO_2 ratios.

Thus, the maximum content of CH_4 in biogas produced from anaerobic digestion can only be about 70% when digestion of oils is included; for typical dairy wastes, a methane content of between 55% and 60% is most likely.

Despite this, it is frequently observed that CH_4 concentrations in biogas from dairy manures are typically somewhat above 60%. There are two mechanisms that can explain such an increase in CH_4 content in the biogas, and these could possibly be used to achieve the goal of increasing methane gas production: two phase digestion and CO_2 dissolution in the process water. These are discussed below.

Two-Phase Anaerobic Digestion

Two-phase anaerobic digestion processes have been extensively studied and in a few cases also applied in practice. In such processes, two bioreactors are operated in series, with the initial reactor operated at a much shorter hydraulic retention time (HRT), as little as one tenth or less of the HRT used in a typical single-stage reactor. The second reactor is operated at typical anaerobic digestion HRT, generally over 15 days. Thus, the first reactor is much smaller than the second reactor, in which nearly all conversion to methane occurs.

The essential concept of two-phase digestion is to separate the two main microbiological processes of anaerobic digestion, acidogenesis (production of volatile fatty acids, H_2 and CO_2) and methanogenesis (production of methane from the fatty acids, H_2 and CO_2). These two reactions are carried out by distinct bacterial species and populations, and the two-phase anaerobic digestion process is based on the concept that the operational characteristics of each stage can be adjusted to favor the bacteria: very short HRTs and solids retention times (SRTs), with resulting organic-acid formation and low pH in the first stage; longer HRTs and conversion of the acids to methane (and CO_2) at neutral pH in the second. Thus the aim is to provide an optimal environment for each of these distinct microbial populations, thus allowing an overall faster reaction (e.g., reducing the reactor size of the combined first and second stage compared to conventional systems). Two-phase digestion is also claimed to result in a greater overall yield of methane, as a larger fraction of the substrates will be metabolized and converted to biogas, presumably by action of the more vigorous acidogenic bacteria.

Unfortunately, this concept suffers from a fundamental flaw: the two types of populations work commensally, that is they depend on each other for optimal metabolism. Simply put, the H_2 and acetate (as well as the higher fatty acids) produced by the acid-forming bacteria are strong inhibitors of the metabolism by these bacteria. The methanogens, by removing these “waste” products and converting them to CH_4, perform a most useful and necessary role in the overall process. Indeed, although acidogenic bacteria (at least some populations) tolerate the low pH that develops in the first, short hydraulic retention time, acid-forming reactor of a two-phase process, a low pH does not actually help the process of acidogenesis. In brief, after several decades of research, the advantages of two-phase anaerobic digestion are still to be demonstrated. Indeed, the main advantage claimed for two-phase digestion, the reduction in overall tank sizes, has not been demonstrated, and the operation of two, rather than one, digesters is not an advantage.

It should be noted in this context that many, and in practice perhaps most, of so-called two-phase processes, are in actuality, two-stage processes, where the first stage also produces methane. In these cases the volume ratio of the first and second stages is greater than the approximately 1:10 (or even 1:20) of the second stage, typical of two-phase digestion. Essentially in two-stage processes the first stage acts mainly as a surge tank, sometimes with a liquid recycle loop from the second to the first stage, which would actually defeat the objective of two-phase digestion. Two-stage digestion does, however, reduce short-circuiting, a significant issue with single-stage mixed tank reactors.

For a two-phase digestion, the ideal stoichiometry, for the simple case of carbohydrate breakdown, can theoretically be written as:

First stage: $C_6H_{12}O_6 + 2\ H_2O \rightarrow 4\ H_2 + 2\ C_2H4O_2$ (acetic acid) $+ 2\ CO_2$ (4)

Second stage: $2\ C_2H_4O_2 \rightarrow 2\ CH_4 + 2\ CO_2$ (5)

Overall this does not improve the biogas methane content and reduces methane yields by one third, though it produces an equivalent amount of H_2 fuel.

A great deal of research is ongoing to achieve such a yield of H_2 in the first stage, due to the current popularity of H_2 as a fuel. However, in practice, such high yields would be achievable only under extreme laboratory conditions (e.g., with a large amount of purge gas, to strip H_2 from the first stage, and the use of very high temperature strains, at 180º F). The best H_2 yield that is actually obtained and obtainable is about half this, with the remainder of the sugar substrate being converted into more reduced products (e.g., propionic acid, butyric acid, ethanol, etc.):

First stage: $C_6H_{12}O_6 \rightarrow C_4H_8O_2$ (butyric acid) $+ 2\ CO_2 + 2\ H_2$ (6)

Second stage; $C_4H_8O_2 + H_2O \rightarrow 2.5\ CH_4 + 1.5\ CO_2$ (7)

This raises the content of the methane in the biogas from the second stage to a little over 60% (for this illustrative case), but at a decreased yield of methane (e.g., 2.5 vs. 3 in a single-phase process). Depending on the operating conditions of the first phase, virtually no H_2 is produced in the first stage, resulting in a production of only CO_2 in the first stage and more methane in the second stage. However, in this case the actual amount of net CO_2 produced in the first stage is also reduced, and, thus, no further increase in biogas CH_4 content is likely (although theoretically an increase of up to 75% could be possible).

In principle it would be possible to increase the CH_4 content of biogas by feeding the H_2 produced by the first-phase reactor to the second-phase reactor. Methanogenic bacteria, which dominate the second phase, use H_2 preferentially and at very high rates, converting CO_2 into CH_4. However, this process would only be effective in raising CH_4 content if the H_2 and CO_2 produced in the first stage were separated, which would defeat the purpose of avoiding such separation processes.

In any event, a two-phase process is not applicable to dairy wastes. A two-phase process, and the stoichiometric relationships discussed above, are applicable only to soluble and readily metabolized sugars and starches, possibly some fats and protein, but not to the more difficult to digest particulate, fibrous and other insoluble matter that comprise most of the substrates available for bacterial decomposition in dairy wastes. For dairy wastes there would be essentially no H_2 produced in the first phase of a two-phase process. The advantages of two-phase digestion, though a much promoted process, are modest even when applied to more suitable wastes such as food processing wastes, which are high in sugars or starches. The process should not be considered for dairy wastes.

Removal of Carbon Dioxide During the Digestion Process

The second mechanism that can account for the relatively higher CH_4 content in biogas than would be expected from simple stoichiometry is the dissolution of CO_2 in the digester water. CO_2 is much more soluble than CH_4 in water. At 1 atmosphere pressure (about 14 psi) and ambient temperature (e.g., 21º C, or 70º F) about 1.8 grams per liter (g/l) of CO_2 are dissolved in water compared to about 4 mg/l of CH_4. Gas solubility is proportional to partial pressure, thus, at a 50/50 CH_4:CO_2 ratio, these concentrations would be halved but the relative ratios of the two gases dissolved in water would be the same. This ratio of 400 to 1 between CO_2 to CH_4 dissolution in water is the basis for the water scrubbing process for CO_2 removal (see Chapter 3 of main report). It also accounts for the rather significant amount of CO_2 that exits the digesters dissolved in water and, thus, the enrichment in CH_4 observed in the biogas, compared to what is expected from the above stoichiometric equations.

This can be exemplified by a simple calculation: Assume that a dairy waste with 4 g/l of degradable VS (volatile solids), of which 50% is C, is stoichiometrically (molar basis) converted to equal amounts of CO_2 and CH_4. This would produce 3.7 g/l of CO_2 and 1.25 g/l of CH_4. As more of the CO_2 would remain dissolved in the water, the actual ratio of CO_2: CH_4 in the liquid phase would, at equilibrium, be only about 2 mg of CH_4, a negligible amount, but 0.7 g/l of CO_2, which reduces the amount of CO_2 in the gas phase, from 50/50 to about 55/45 CH_4:CO_2.

In practice, the effluent from a digester is not at equilibrium with the atmosphere above it (e.g., the biogas); more CO_2 and CH_4 are dissolved in the liquid than expected at equilibrium. Although disequilibrium would affect dissolved CO_2 and CH_4 about equally, because of the much higher solubility of CO_2 than CH_4 in the liquid, the recovered biogas would be more enriched in CO_2 than calculated above for the equilibrium case. The "extra" CO_2 (and CH_4) dissolved in the liquid effluent from the digesters would be released to the atmosphere after the liquid effluent leaves the digester. This could more than double the amount of CO_2 produced during the anaerobic digestion process that does not actually enter the biogas phase. In the above example, if the amount of CO_2 dissolved in the water phase were three times higher than at equilibrium, this would give a 2:1 ratio of CH_4:CO_2 in the gas phase, with half the CO_2 produced remaining in the liquid phase. At the same relative disequilibrium, CH_4 losses in the liquid effluent would still be less than 1% of the total produced. A three-fold excess (above that equilibrium with the gas phase) in dissolved gases is well within what is possible for full-scale anaerobic digestion processes. It should, however, be noted that the very long retention times typical of anaerobic digestion processes, in particular dairy manures, means that there is more time for the gas and liquid phase to reach equilibrium. Thus, although the maximum ratio of CH_4:CO_2 that could be achieved just from CO_2 being dissolved in the liquid effluent from the AD process is not clear, it is not likely that it would be much higher than the above projected 2:1 ratio. As this ratio increases the disequilibrium between liquid and gaseous phases increases sharply.

This issue of CO_2 dissolution and disequilibrium has been somewhat neglected in most anaerobic digestion studies, but it can readily account for the frequent observations of relatively high CH_4:CO_2 ratios in biogas in many systems, including from dairy manures, compared to predictions from stoichiometry and equilibrium calculations. Although it does not appear likely that a much higher than 2:1 ratio would actually be achievable, this issue deserves further study.

It should be noted that for laboratory-scale and even small pilot plants, the amount of mixing (agitation) that the bioreactors are normally subjected to is many times greater per unit volume than for large-scale processes, Thus, small, well-mixed systems are typically run much more closely near the gas exchange equilibrium than would be the case for full-scale systems. Consequently, in respect to the ratio of gases in the biogas produced, it is not possible to directly extrapolate laboratory results to full-scale systems.

In a few cases, very high CH_4:CO_2 ratios, about 9:1, have been reported from anaerobic digester processes. These did not involve standard anaerobic digester reactor designs but, rather gas collected from anaerobic lagoons. In these situations, the gas, collected either at the surface or below, was exposed to large amounts of liquid. In particular these reports originate from algal wastewater treatment systems, where algae deplete the water of CO_2, providing a sink for CO_2 produced by the anaerobic digestion process. Thus, in reality, such systems combine anaerobic digester with a water scrubbing process. Although algal ponds can be used for treating anaerobic digester effluents (BOD removal and nutrient capture) and can be of interest in dairy manure management, this technology is still in the development stage. Also, it is not likely that this technology would be as closely integrated with an anaerobic digester process as suggested by proponents of using an in-pond digester process and submerged gas catchers. The most plausible system configuration separates these processes of anaerobic digester and effluent treatment, if required. In any event, this topic is beyond the scope of the present report.

Conclusions

Biogas produced by dairy wastes in typical AD processes is somewhat enriched in CH_4, compared to what would be expected from the metabolic processes of organics degradation. However, the observed and expected enrichment is rather modest, from about 50% to 55% or 60%. There is also a near-doubling of CH_4 to CO_2 ratios, from 1:1 closer to 2:1 (e.g., 66% methane), which is about the maximum that would likely be achievable.

For applications where CO_2 removal is required (e.g., for upgrading to vehicular fuels), CH_4 to CO_2 ratios of over 10:1, typically even above 20:1, would be required. This suggests that there is little point in trying to improve on the anaerobic digester process in this regards, as a CO_2 removal process would not be avoided if the goal is for a higher purity CH_4 fuel. Also, it does not appear that the additional effort that would be required to increase CH_4:CO_2 ratios during the anaerobic digester process could be justified by any savings in the final purification step. Thus, producing a high CH_4 content biogas from dairy manures directly from the anaerobic digestion process is not practical and would not significantly decrease the costs of CO_2 removal required for applications requiring biomethane quality fuel. Thus, post-digestion processes for upgrading biogas to renewable methane should be the main focus.

Appendix B

Detailed Description of the Three Main Dairy Digester Technologies

This appendix reviews and compares covered-lagoon, plug-flow, and complete-mix anaerobic digestion technologies for the quantity and quality of renewable biogas produced. It also presents detailed information and design considerations of these three anaerobic digester technologies available for dairy farms in California.

Description of Covered Lagoon Digester

A cover can be floated on the surface of a properly sized anaerobic lagoon receiving flush manure to recover methane. The most successful arrangement includes two lagoons connected in series to separate biological treatment for biogas production and storage for land application. A variable volume one-cell lagoon designed for both treatment and storage may be covered for biogas recovery. However, a single-cell lagoon cover presents design challenges not found in constant-volume lagoons and will require assistance of professionals familiar with the design, construction and operation of these systems. Figure B-1 shows the components of a covered lagoon digester; Figure B-2 shows an actual system operating in California.

The primary lagoon is anaerobic and operated at a constant volume to maximize biological treatment, methane production, and odor control. The biogas recovery cover is floated on the primary lagoon. Ideally, manure contaminated runoff is bypassed to the secondary lagoon. The secondary lagoon is planned as variable volume storage to receive effluent from the primary lagoon and contaminated runoff to be stored and used for irrigation, recycle flushing, or other purposes.

Temperature is a key factor in planning a covered lagoon. Warm climates require smaller lagoons and have less variation in seasonal gas production. Colder temperatures in northern California will reduce winter methane production. To compensate for reduced temperatures, loading rates are decreased and hydraulic retention time (HRT) is increased. A larger lagoon requires a larger, more costly cover than a smaller lagoon in a warmer climate. Reduced methane yield may decrease the return on investment.

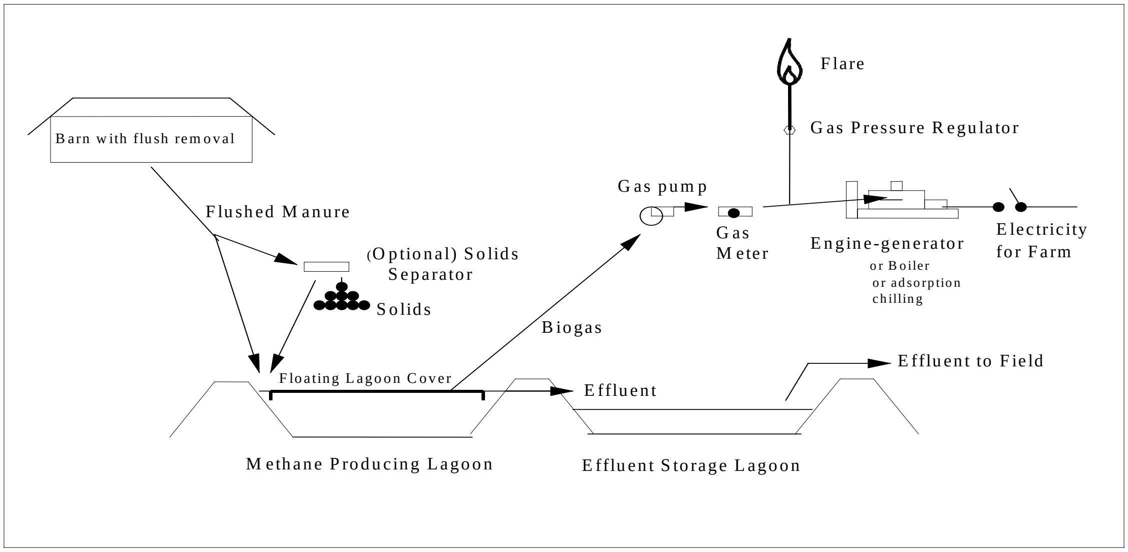

Figure B-1 Covered lagoon system components

Figure B-2 Photograph of Castelanelli Bros. Dairy covered lagoon digester located in Lodi, CA. (source: RCM Digesters, Inc.)

Components of Covered-Lagoon Digester

Solids separator. A gravity solids trap or mechanical separator should be provided between the manure sources and the lagoon.

Lagoons. Two lagoons are preferred; a primary anaerobic waste treatment lagoon and a secondary waste storage lagoon.

Floating lagoon cover. The most effective methane recovery system is a floating cover over all or part of the primary lagoon.

Biogas utilization system. The recovered biogas can be used to produce space heat, hot water, cooling, or electricity.

Covered-Lagoon Design Variables

Soil and foundation. Locate the lagoons on soils of slow-to-moderate permeability or on soils that can seal through sedimentation and biological action. Avoid gravelly soils and shallow soils over fractured or cavernous rock.

Depth. The primary lagoon should be dug where soil and geological conditions allow it to be as deep as possible. Depth is important in proper operation of the primary lagoon and of lesser importance in the secondary lagoon. Deep lagoons help maintain temperatures that promote bacterial growth. Increased depth allows a smaller surface area to minimize rainfall and to cover size, which reduces floating cover costs. The minimum depth of liquid in the primary lagoon should be 12 ft.

Loading rate, hydraulic retention time and sizing of primary lagoon. The primary anaerobic lagoon is sized as the larger of volatile solids loading rate (VSLR) or a minimum HRT. The VSLR is a design number, based primarily on climate, used to size the lagoon to allow adequate time for bacteria in the lagoon to decompose manure.

Volatile solids loading rate. Figure B-3 below shows isopleths for the appropriate loading rates for a constant volume primary lagoon in a two-cell lagoon system.

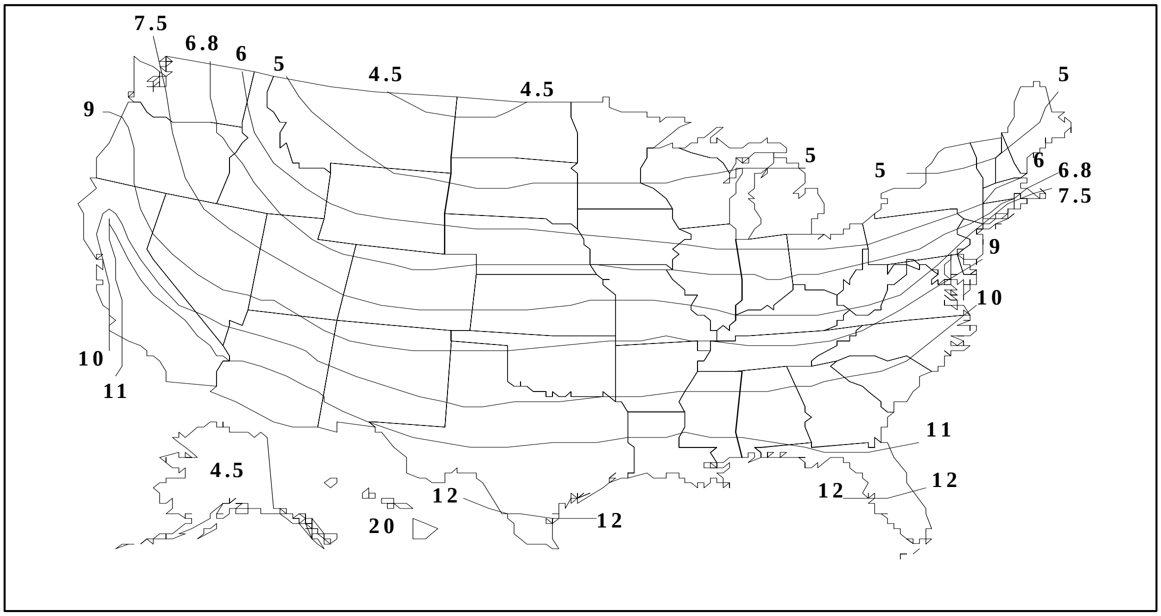

Figure B-3 Covered Anaerobic Lagoon Maximum Loading Rate (lb VS/1,000 ft^3/day) (NRCS, 1996, Code 360, Reference 3)

Minimum hydraulic retention time. The VSLR procedure is appropriate in most cases, however modern farms using large volumes of process water may circulate liquids through a primary lagoon faster than bacteria can decompose it. To avoid this washout, a minimum hydraulic retention time (MINHRT) is used to size the lagoon. Figure B-4 shows MINHRT isopleths.

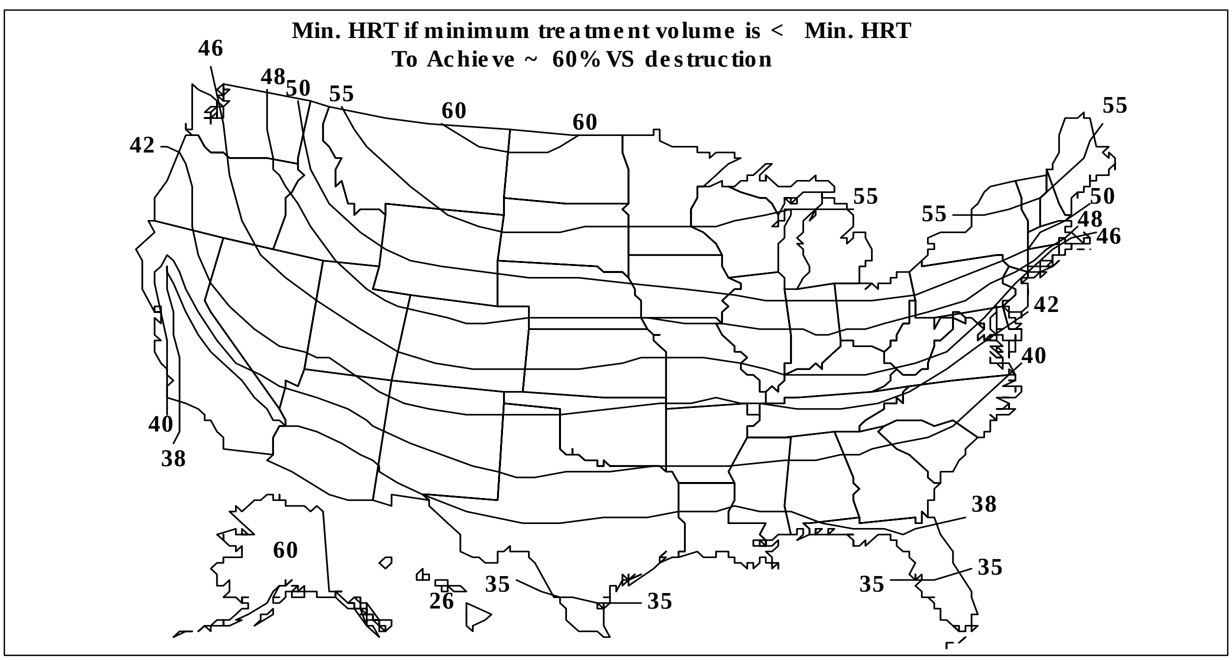

Figure B-4 Covered anaerobic lagoon minimum hydraulic retention times (NRCS, 1996, Code 360, Reference 3)

Primary lagoon inlet and outlet. The primary lagoon inlet and outlet should be located to maximize the distance across the lagoon between them.

Rainfall. Rainfall is not a major factor in determining the potential success of a covered lagoon. In areas of high rainfall, a lagoon cover can be used to collect clean rain falling on the cover and pump it off to a field. In areas of low rainfall, a lagoon cover will limit evaporation and loss of potentially valuable nutrient rich water.

Cover materials. Many types of materials have been used to cover agricultural and industrial lagoons. Floating covers are generally not limited in dimension. A floating cover allows for some gas storage. Cover materials must be: ultraviolet resistant; hydrophobic; tear and puncture resistant; non-toxic to bacteria; and have a bulk density near that of water. Availability of material, serviceability and cost are factors to be considered when choosing a cover material. Thin materials are generally less expensive but may not have the demonstrated or guaranteed life of thicker materials. Fabric reinforced materials may be stronger than unreinforced materials, but material thickness, serviceability, cost and expected life may offset lack of reinforcement.

Cover installation techniques. A lagoon cover can be installed in a variety of ways depending upon site conditions. Table B.1 lists features found in floating methane recovery lagoon covers. Figure B-5 shows typical features of lagoon covers.

Table B-1 Features of a Floating Methane Recovery Lagoon Cover

Feature	Description
Bank Attachment Options	See text and Figure B-5.
Rainfall Management	Rainfall may be pumped off the cover or drained into the lagoon.
Securing Edges of a Floating Cover	The edges of the cover can be buried in a perimeter trench on the lagoon embankment or attached to a concrete wall. Floating edges not secured directly on the embankment need support in place. A corrosion resistant rope or cable is attached to the cover as a tie-down and tied to an anchor point.
Skirting	Portions of the cover floating in the lagoon require a perimeter skirt hanging into the lagoon from the cover.
Anchor Points	Anchor points for cable or rope may be driven metal stakes or treated wood posts.
Float Logs	A grid of flotation logs is attached to the underside of the cover. The float logs may be necessary as gas collection channels, to minimize gas pockets and bubbles under the cover.
Weight Pipes	A grid of weight pipes may be laid on the cover surface to help hold the cover down.
Gas Collection	Biogas bubbles to the surface of the lagoon and migrates across the underside of the cover. A gas pump maintains a vacuum under the cover. A gas collection manifold is attached to the cover. A gastight through-the-cover, through-the-attachment wall or under the buried cover gas pipe carries biogas to a biogas utilization system.

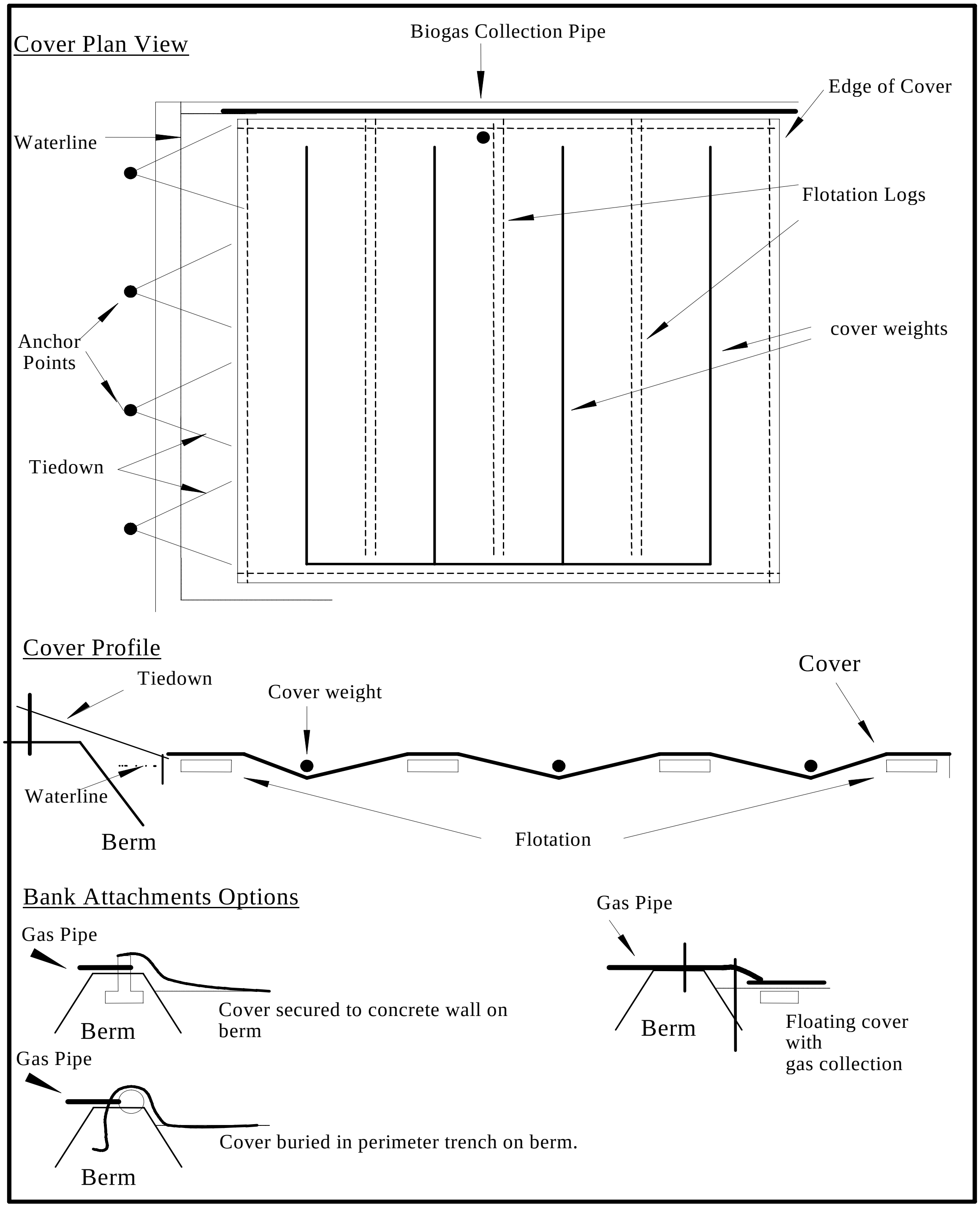

Figure B-5 Typical features of lagoon covers

Full perimeter attachment. The entire lagoon surface is covered and the edges of the material are all attached to the embankment.

Completely floating or partially attached cover. The cover may be secured on the embankment on one to three sides or the whole cover can float within the lagoon. All or some of the sides may stop on the lagoon surface rather than continuing up the embankment.

Operation and Maintenance of Covered-Lagoon Digester

The operation and maintenance of a covered lagoon should be relatively simple.

Primary lagoon — operation. The proper design and construction of a primary lagoon leads to a biologically active lagoon that should perform year round for decades. Any change in operation will most likely be due to a change in farm operation resulting in an altered volatile solids loading or hydraulic load to the lagoon. The owner should make a visual inspection of lagoon level weekly.

Primary lagoon — maintenance. Minimal maintenance of the primary lagoon is expected if the design volatile solids and hydraulic loading rates are not changed. Lagoon banks should be kept free of trees and rodents that may cause embankment failure. Weeds and cover crops should be cut to reduce habitat for insects and rodents. Occasional plugging of inlet and outlets can be expected. Sludge accumulation may require sludge removal every 8 to 15 years. Sludge can be removed by agitating and pumping the lagoon or by draining and scraping the lagoon bottom.

Cover operation. Operating a lagoon cover requires removing the collected biogas from below the cover regularly or continuously. Large bubbles should not be allowed to collect. If the cover is designed to accumulate rainfall for pumpoff, accumulated rainwater should be pumped off.

Cover maintenance. The cover should be visually inspected weekly for rainwater accumulation, tearing, wear, and proper tensioning of attachment ropes. The rainwater pumpoff system should be checked after rainfall and maintained as needed.

Description of Plug-Flow Digester

A plug-flow digester is used to digest manure from ruminant animals (dairy, beef, sheep) that can be collected as a semisolid (10% to 60% solids) daily to weekly with minimal contamination (dirt, gravel, stones, straw) and delivered to a collection point.

Components of Plug-Flow Digester

A plug-flow digester system generally includes a mix tank, a digester tank with heat exchanger and biogas recovery system, an effluent storage structure, and a biogas utilization system. Post digester solids separation is optional. Figure B-6 shows the features of a plug-flow digester system.

Collection/mix tank. A mix tank as described above for a complete digester is used to achieve a solids concentration between 11% and 14% solids.

Plug-flow digester. A plug-flow digester is a heated, in-ground concrete, concrete block or lined rectangular tank. The digester can be covered by a fixed rigid top, a flexible inflatable top or a floating cover to collect and direct biogas to the gas utilization system.

Biogas utilization system. The recovered biogas can be used to produce space heat, hot water, cooling, or electricity.

Solids separator (optional). A mechanical separator may be installed between the plug-flow digester outflow and the effluent storage structure.

Design Criteria and Sizing the Plug-Flow Digester

Location. If a manure pump is installed to pump the 12% solids manure, the digester can be located within a 300 ft radius of the mix tank at a convenient location with good access.

Mix tank. The mix tank can be round, square, or rectangular. A pump may be required to move manure to the plug flow digester.

Hydraulic retention time and sizing of plug-flow digester. A plug-flow digester will function with an HRT from 12 to 80 days. However, an HRT between 15 and 20 days is most commonly used to economically produce 70% to 80% of the ultimate methane yield.

Dimensions. The depth of a plug-flow digester can be between 8 feet and 16 feet depending upon soil conditions and the required tank volume. The width:depth ratio is usually greater than 1 and less than 2.5. The length:width ratio should be between 3.5 and 5.

Heat exchanger: An external heat exchanger or an internal heat exchanger is required to maintain the digesting mixture at the design temperature. Hot water circulated through the heat exchanger is heated using biogas as a fuel for a boiler or waste heat from a biogas fueled engine-generator.

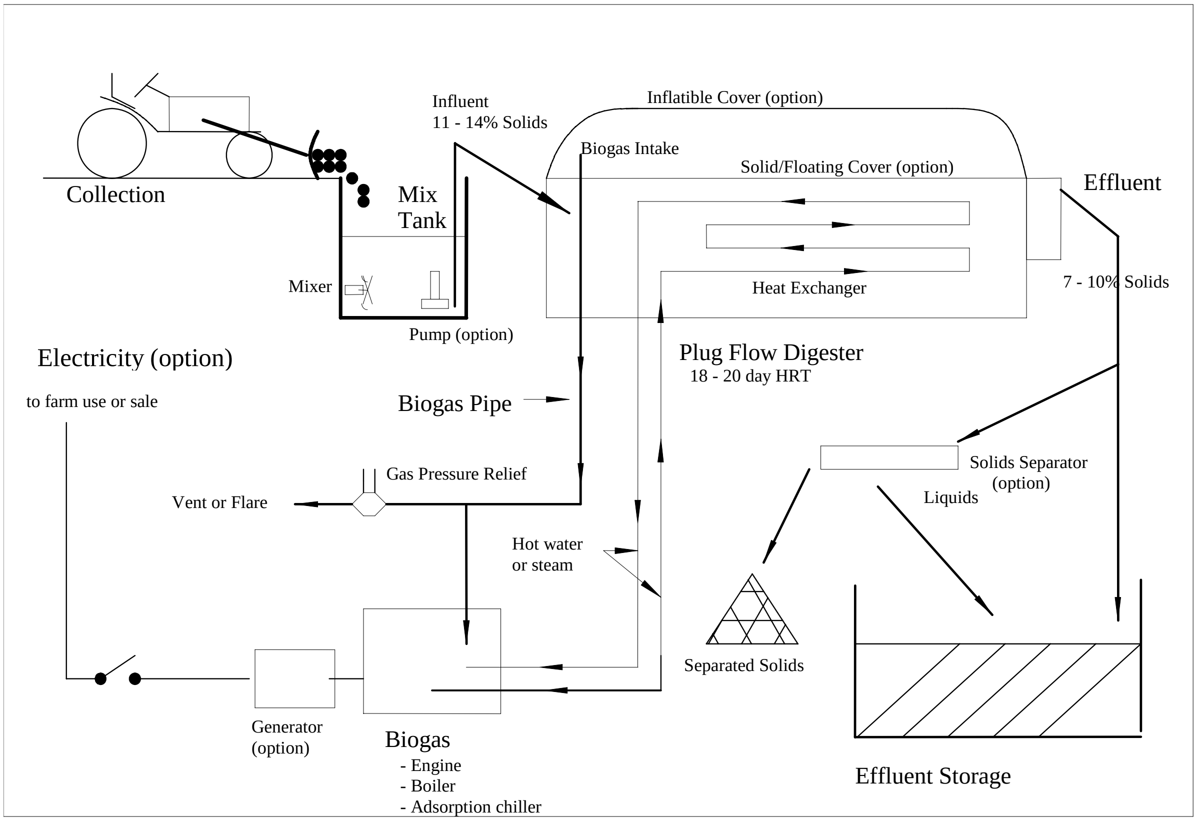

Figure B-6 Features of plug-flow digester system

Operating temperature. The daily temperature fluctuation should be less than 1^o F. Most plug flow digesters operate in mesophilic range between 95^o to 105^o F with an optimum of 100^o F. It is possible to operate in the thermophilic range between 135 to 145^o F, but the digestion process is subject to upset if not closely monitored.

Insulation. A plug flow digester surface may be insulated to control heat loss.

Construction materials. The digester can be constructed as a lined trench or as a reinforced concrete or block tank.

Methane recovery system and covers. See discussion of methane recovery system above under complete mix digesters.

Description of Complete-Mix Digester

A complete-mix digester is a controlled temperature, constant volume, mechanically mixed, biological treatment unit that anaerobically decomposes medium concentration (3% to 10% solids) animal manures and produces biogas (60% methane and 40% carbon dioxide) and biologically stabilized effluent. Figure B-7 includes general features of a complete-mix digester system.

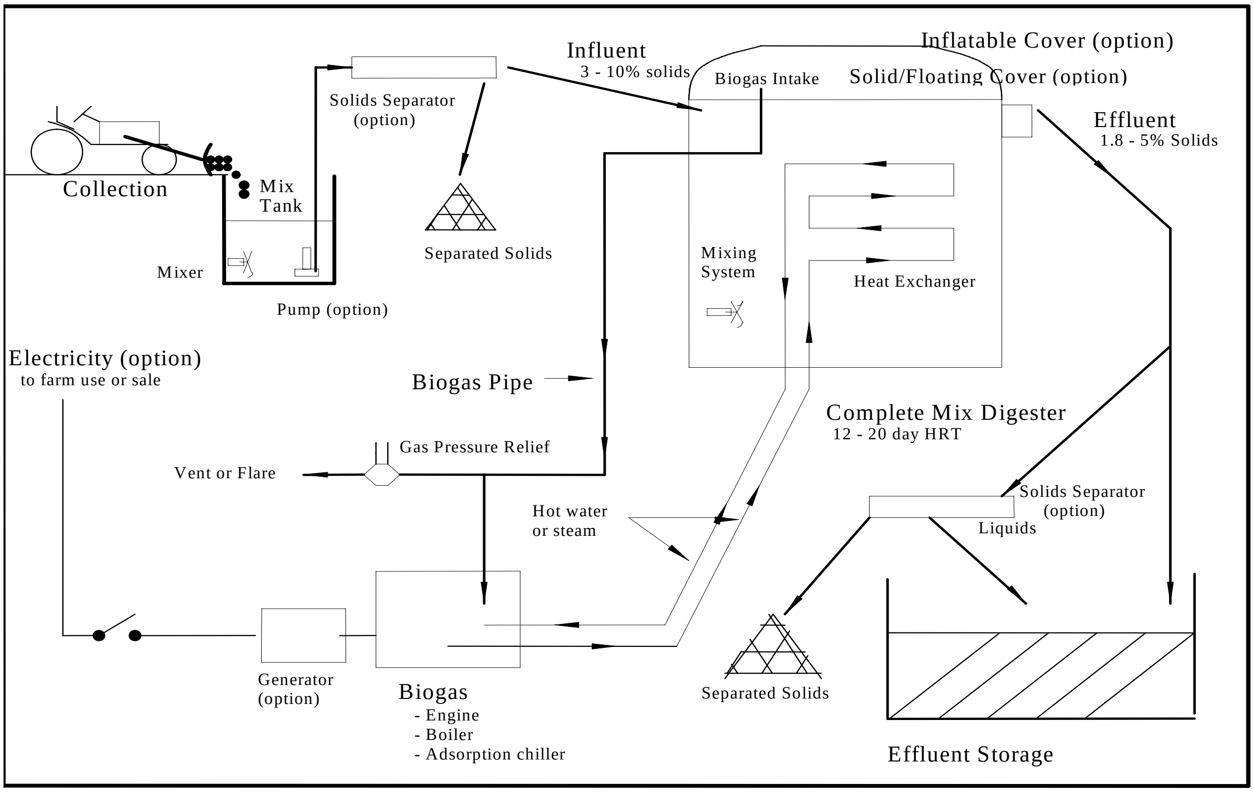

Figure B-7 Components of complete-mix digester

A complete-mix digester is designed to maximize biogas production as an energy source. The optimized anaerobic process results in biological stabilization of the effluent and odor control. The process is part of manure management system and supplemental effluent storage is usually required. Manure contaminated rainfall runoff or excess process water should not be introduced into the complete-mix digester.

Components of Complete-Mix Digester

The components of a complete-mix digester system generally include a mix tank, a digester tank with mixing, heating and biogas recovery systems, an effluent storage structure, and a biogas utilization system. Pre- or post-digester solids separation is optional.

Mix tank. The mix tank is a concrete or metal structure where manure is deposited by a manure collection system. It serves as a control point where water can be added to dry manure or dry manure can be added to dilute manure. Manure is mixed to 3% to 10% solids content prior to introduction into the complete-mix digesters.

Pretreatment. A solids separator may be used to separate solids from influent manure to reduce solids buildup in the digester.

Complete-mix digester. A complete-mix digester is a heated, insulated above ground or in-ground circular, square or rectangular tank with a mixing system. The tank is covered by a fixed solid top, a flexible inflatable top, or a floating cover to collect and direct biogas to the gas utilization system. All covers are gas tight.

Biogas use. The recovered biogas can be used to produce space heat, hot water, cooling, or electricity.

Solids separator (optional): A mechanical separator may be installed after a complete-mix digester to capture fibrous materials fed as roughage to ruminants.

Complete-Mix Digester Design Criteria

Location: A complete-mix digester can be located within a 600 ft radius of the mix tank at a convenient location with good access.

Optimum solids concentration. The operating range for influent solids concentration in a complete-mix digester is 3% to 10% solids. However, 6% to 8% solids is the preferred concentration.

Mix tank. The mix tank can be round, square, or rectangular. A pump may be required to move manure to the digester.

Hydraulic retention time and sizing of complete-mix digester. A complete-mix digester will function with an HRT from 10 to 80 days. However, an HRT between 12 and 20 days is most commonly used to economically produce 60% to 75% of the ultimate methane yield.

Operating temperature. A heat exchange system should maintain the daily temperature fluctuation at less than 0.55^{o} C (1^{o} F). Most complete-mix digesters operate in the mesophilic range between 35^{o} to 41^{o} C (95^{o} to 105^{o} F). It is possible for this type of digester to operate in the thermophilic range between (135^{o} to 145^{o} F) but the digestion process is subject to upset if not closely monitored.

Insulation. A complete-mix digester tank may require insulation to control heat loss.

Heat exchanger. An external heat exchanger or an internal heat exchanger is used to heat and maintain the digesting mixture at the design temperature. Hot water or steam circulated through the heat exchanger is heated using a biogas-fueled boiler or waste heat from a biogas fueled engine-generator.

Construction materials. The digester tanks can be concrete or metal.

Mixing. Gas or mechanical mixing is used to stir the digester.

Dimensions. The depth can be between 8 and 40 ft depending upon soil conditions and the required tank volume.

Methane recovery system. A complete-mix digester is covered by a gas tight fixed solid top, a flexible top, or a floating cover to collect and direct biogas to the gas utilization system.

Solid cover. A solid cover is constructed to avoid cracking and leaks. Solid covers should resist corrosion. A solid cover allows for minimal gas storage.

Inflatable Cover. A coated fabric is generally used for inflatable covers. An inflatable cover can be designed for some gas storage. Wind protection may be necessary. The cover must have a gas tight seal. These materials are described in the covered lagoon discussion, above.

Floating cover. A floating cover is designed to lie flat on the digester surface. See discussion of floating covers for covered lagoons, above.

Operation and Maintenance of Complete-Mix and Plug-Flow Digesters

Operation and maintenance of complete-mix and plug-flow digesters is very similar and therefore will be discussed together in this section. Proper operation and maintenance of plug-flow and complete-mix digesters is necessary for successful operation.

Mix tank — operation. On a daily or every other day basis, collectible manure is pushed, dragged or dumped into the mix tank. If necessary, dilution water or drier manure is added to the collected manure and mixed to achieve the design total solids mixture. The mixed manure is released via gravity gate or pumped into the digester.

Mix tank — maintenance. Mix tank maintenance consists of normal maintenance of pumps and mixers per manufacturers recommendations. The mix tank will require occasional cleaning to remove accumulated sand, gravel, steel and wood.

Complete-mix and plug-flow digester — operation. A complete-mix digester is fed hourly to daily, displacing an equal amount of manure from the outlet. A plug-flow digester is fed from the mix tank daily or every other day. The digester heating and mixing system should be checked daily to verify operation.

Complete-mix and plug-flow digester — maintenance. The digester temperature should be checked daily. The effluent outlet and digester gas pressure relief should be checked weekly to be sure that they are operating properly. The heat exchanger pump should be lubricated per the manufacturer’s recommendations. The mixer in a complete mix digester should be lubricated per the manufacturer’s recommendations. Sludge accumulation may require sludge removal every 8 to 10 years.

Cover — maintenance. The cover should be visually inspected weekly for rainwater accumulation, cracks, tearing, wear, and tensioning.

Appendix C

Conversion of Biogas to Biomethanol

Interest in neat methanol as a vehicular fuel has been steady for many years; the “Methanol Institute” promotes this chemical and major energy (oil, gas) companies also have some interest in this fuel. There are claims that methanol-using internal combustion engines reduce air pollution. Methanol is now also being considered as a storage fuel for hydrogen fuel cell cars. Nevertheless, during the past 20 years, no significant market has developed for methanol as fuel, although it is often used as an additive and can be blended with biodiesel to enhance cold weather properties. Methanol has only half the energy content of gasoline; it has a lower vapor pressure than gasoline; it can attack fuel and engine components; and it is toxic. Although these obstacles could be overcome, together with the lack of a methanol vehicle fueling infrastructure, they have limited the potential of this fuel.

Past Unrealized Projects

One company (TerraMeth Industries, Inc. of Walnut Creek, California) proposed building a landfill-gas-to-methanol plant in West Covina, Southern California during the 1990s. Despite legislation that supported the project and several years of trying to find financing, this project did not come to fruition. Another proposed project in Washington State was also abandoned. With the phase-out of MTBE, interest in methanol production waned.

The process for converting dairy manure biogas to biomethanol is challenging, primarily because it would need to be carried out at a scale several orders of magnitude smaller than current processes. For example, the unrealized TerraMeth landfill-gas-to-methanol project would have cost just under $10 million (capital costs) for a facility that produced about 6 million gallons of methanol per year (and this cost is judged optimistic by many who have examined this conversion). An equivalently sized dairy facility would need over 50,000 cows to produce this much gas, which, by industrial standards is actually a very small plant.

The Smithfield Foods Utah Project: From Hog Manure to Biodiesel

A recent example of an animal-manure-to-methanol project is one proposed by Smithfield Foods in Utah. A subsidiary firm, Best Fuels LLC, announced an ambitious $20-million project that would convert the manure from 23 hog farms (with a total of 257,000 finisher pigs) first to biogas and then to methanol for biodiesel production (Figure C-1). The farms were all within a 5-mile radius and the impetus for the project was the difficulty of marketing electricity from biogas produced from the animal manure.

As shown in Figure C-1, manure (about 40,000 tons dry matter/year) collected from swine houses is pumped to a central location, thickened by gravity to about 4.5% solids and digested in inground, heated (95 °F), floating cover digesters. The facility would produce about 1.2 million ft^3/day of biogas.

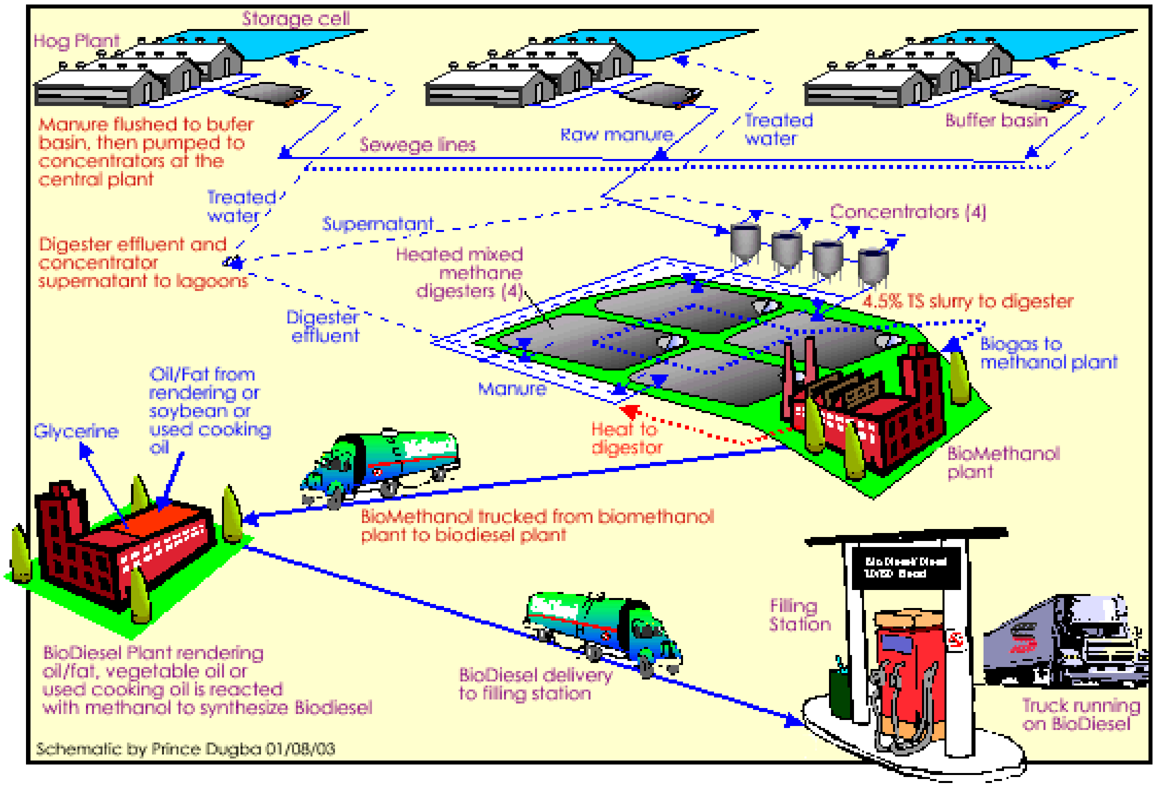

Figure C-1 Project of Best Fuels LLC/Smithfield Foods for Converting Hog Manure to Methanol

The biogas is next pumped to a central plant, where H_2S is removed with sodium hydroxide (NaOH). The gas is converted to methanol in a conventional steam-reforming/water-gas shift reaction followed by high-pressure catalytic methanol synthesis:

$CH_4 + H_2O \dashrightarrow CO + 3H_2$ and $CO + H_2O \dashrightarrow CO_2 + H_2$ gasification/shift reaction (1)

$CO + 2H_2 \dashrightarrow CH_3OH$ or $CO_2 + 3H_2 \dashrightarrow CH_3OH + H_2O$ methanol synthesis reactions (2)

The process at the Smithfield site is expected to yield 7,000 gallons of methanol per day. The methanol is used off-site for biodiesel production, expected to yield 40,000 gallons of biodiesel per day. The project literature states, “These processes should be considered industrial-scale processes, thus requiring a highly trained staff and high-tech equipment.”

However, after the initial much publicized announcement of the project no further information has become available. It is the opinion of the authors that if such an approach were even modestly economically attractive, it would have already been implemented under the much more favorable (from an engineering standpoint) opportunities made possible at stranded high-CO_2 natural gas wells. There the quality, quantity, pressure of the gas would much better justify their upgrading and conversion to methanol. It remains to be seen if this project actually moves forward.

Appendix D

Compressed Natural Gas and Liquefied Natural Gas Vehicles Available in California

CNG Vehicles

In 2004, the following types of CNG and LNG vehicles were available in California.

Light-Duty CNG Vehicles

The following types of light-duty CNG vehicles are currently available in California:

- Passenger vehicles
- Pickup trucks
- Passenger vans (including light-duty shuttles)
- Cargo vans

Light-duty CNG vehicle models are currently available from Honda, General Motors, Daimler-Chrysler and Baytech (a CNG vehicle converter specializing in GM vehicles). Ford, which had previously offered several CNG models (including the Crown Victoria sedan used in many CNG taxi fleets), announced in February, 2004 that they were stopping production of all CNG vehicles.

Examples of representative light-duty CNG vehicle types are shown below:

Passenger Vehicles

Honda Civic GX
American Honda Motor Co., Inc.
Four-door dedicated CNG sedan; auto CVT; 1.7L four cylinder; 8 GGE fuel capacity; 200 mile range
Certification: SULEV

Pickup Trucks

Chevrolet Silverado C2500 Pickup
General Motors Corp.
Dedicated CNG pickup truck; 2WD; 4-speed automatic; regular, extended cab or crew cab; 6.0L V8; 15 GGE fuel capacity; 180 mile range
Certification: ULEV

Passenger Vans

GMC Savana Van
General Motors Corp.
Dedicated CNG van; 8 – 12 passengers; 6.0L V8; 4-speed auto; 20.3 GGE fuel capacity; 320 mile range
Certification: ULEV

Cargo Vans

Chevrolet Express Cargo Van
Baytech Corp.
Dedicated CNG van; 258 ft^3 cargo space; 6.0L V8; 4-speed auto; 20.3 GGE fuel capacity; 320 mile range
Certification: ULEV

Medium- and Heavy-Duty CNG Vehicles

The following types of medium- and heavy-duty CNG vehicles are currently available in California:

- Transit buses
- School buses
- Refuse trucks
- Street sweepers
- Shuttles (medium-duty)
- Trolleys
- Miscellaneous heavy-duty trucks

Medium- and heavy-duty CNG vehicle models are currently available from a variety of truck manufacturers- and vehicle converters. Examples of representative medium and heavy-duty CNG vehicle types are shown below.

Transit Buses

Orion VII CNG
Orion Bus Industries
Dedicated CNG transit bus; max. 44 passengers; 30' – 40' length; low-floor; GVWR 42,540 lbs.; Detroit Diesel Corp. Series 50G/Cummins CG 280; range 350 miles
Certification: ULEV, CARB Low NOx

School Buses

All American RE
Blue Bird Corporation
Dedicated CNG school bus; max. 66/84 passengers; 33' – 40' length; John Deere 6081H 250 6-cylinder
Certification: CARB Low NOx

Refuse Trucks

LWT Refuse Truck
Crane Carrier Co.
Dedicated CNG low entry tilt (LWT) refuse truck; front loader; Cummins CG 275/280 hp or John Deere 6081H 280 hp 6-cylinder; single/ tandem rear axles; GVWR max. 60,000 lbs.; 70 GGE fuel capacity; 200 mile range
Certification: ULEV, CARB Low NOx

Street Sweepers

Crosswind J
Elgin Sweeper Co.
Dedicated CNG sweeper; recirculating air (vacuum) sweeper; Sterling SC 8000 chassis; Cummins 5.9L BG 195 6-cylinder; GVWR 33,000 lbs.; 8 cu. yd. hopper; 52 GGE fuel capacity
Certification: CARB Low NOx

Shuttles

Crusader
Champion Bus, Inc.
Dedicated CNG transit shuttle; max. 25 passengers; Ford E-450/Chevrolet Express cutaway chassis; 4-speed automatic; GM Vortec 5.4L/6.0L V8; GVWR 14,050 lbs.; 37 GGE fuel capacity; 300 mile range
Certification: ULEV, CARB Low NOx

Trolleys

TR 35 RE
Supreme/Specialty Vehicles Inc.
Dedicated CNG trolley; max. 35 passengers; rear engine; CAP/Cat 3126 dual-fuel; GVWR 31,000 lbs.; 300 mile range
Certification: CARB Low NOx

Miscellaneous Heavy-Duty Trucks

Isuzu NPR HD (chassis)
Baytech Corp.
Dedicated CNG heavy-duty truck; multiple applications, e.g., box trucks, beverage/package delivery, landscaping; 5.7/6.0L V8; 4-speed auto; GVWR 14,500 lbs.; 30 GGE fuel capacity
Certification: ULEV

LNG Vehicle Types

LNG vehicle types are currently limited to heavy-duty vehicles. Common examples of heavy-duty LNG vehicles include transit buses, refuse trucks and Class 8 urban delivery (regional heavy delivery) trucks.

The following types of heavy-duty LNG vehicles are currently available in California:

- Transit buses
- Refuse trucks
- Class 8 urban delivery (regional heavy delivery) trucks

Heavy-duty LNG vehicle models are currently available from a variety of truck manufacturers- and vehicle converters.

Examples of representative heavy-duty LNG vehicle types are shown below:

Transit Buses

NABI 35LFW
North American Bus Industries
Dedicated LNG transit bus; max. 30 passengers; 35' low-floor; GVWR 41,150 lbs.; Detroit Diesel Series 50G/Cummins CG 275; 408 gal. LNG fuel tanks; 350 mile range
Certification: ULEV, CARB Low NOx

Refuse Trucks – Class 8 Urban Delivery

Century Class (chassis)
Freightliner LLC
Heavy-duty dual- fuel (LNG/diesel) Class 8 truck; Caterpillar C-12 410 hp 6-cylinder; GVWR 80,000 lbs.; 120 gal. LNG/60 gal diesel fuel tanks; 430 mile range
Certification: ULEV, CARB Low NOx

Appendix E

Energy Contents / Equivalencies for Natural Gas Fuels versus Electricity

1,000,000	Btu	In	1,000 ft^3	Natural gas / biomethane
3,412	Btu	In	1 kWh	Electricity
3.4 ft^3	Natural gas / biomethane	Same energy as	1 kWh	Electricity
120 ft^3	Natural gas / biomethane	Same energy as	1 gal	Gasoline
140 ft^3	Natural gas / biomethane	Same energy as	1 gal	Diesel
24 ft^3	Natural gas / biomethane	Same energy as	1 gal	CNG/CBM
84 ft^3	Natural gas / biomethane	Same energy as	1 gal	LNG/LBM
13,600 Btu	Natural gas / biomethane	Generates (at 25% efficiency)	1 kWh	Electricity
13.6 ft^3	Natural gas / biomethane	Generates (at 25% efficiency)	1 kWh	Electricity
10,400 Btu	Natural gas / biomethane	Generates (at 33% efficiency)	1 kWh	Electricity
10.4 ft^3	Natural gas / biomethane	Generates (at 33% efficiency)	1 kWh	Electricity
6,800 Btu	Natural gas / biomethane	Generates (at 50% efficiency)	1 kWh	Electricity
6.8 ft^3	Natural gas / biomethane	Generates (at 50% efficiency)	1 kWh	Electricity

Appendix F

Cost of Building Dairy Anaerobic Digesters per Kilowatt

Source Document	Digester Name	Date Built	Type	Cost to Build	Avg kW Generated	Cost/ Avg kW
Lusk	Not Ident	1979	Plug, Slurry	$510,000	182.6	$2,792
Nelson and Lamb	Haubenschild	2000	Plug	$355,000	98.0	$3,621
Moser and Mattocks	Haubenschild	1999	Plug	$329,851	85.0	$3,881
Lusk	Craven Dairy	1997	Plug	$247,450	78.3	$3,161
Moser and Mattocks	Craven Dairy	1996	Plug	$287,300	78.3	$3,670
Moser and Mattocks	AA Dairy	1997	Plug	$295,700	70.0	$4,224
Lusk	Fairgrove Farms	1981	Plug	$150,000	60.2	$2,491
Mattocks	AA Dairy	1998	Plug	$280,000	57.1	$4,906
Mattocks	Haubenschild	1999	Plug	$290,000	57.1	$5,081
Lusk	Foster Brothers	1982	Plug	$300,000	54.8	$5,475
Lusk	Cushman Dairy	1997	Comp Mix	$450,000	52.8	$8,523
Lusk	AA Dairy	1998	Plug	$343,300	50.5	$6,796
Lusk	Cooperstown	1985	Comp Mix	$500,000	37.1	$13,477
Lusk	Langerwerf	1982	Plug	$200,000	34.2	$5,840
Lusk	Kirk Carrell Dairy	1998	Plug	$100,000	30.0	$3,337
Lusk	Oregon Dairy	1983	Slurry	$120,000	25.7	$4,672
Moser and Mattocks	Cal Poly	1999	Lagoon	$230,000	19.4	$11,852
Lusk	Agway	1981	Slurry	$175,000	16.8	$10,393
Average dairy digesters over 50 kW						**$4,552**

Source: Lusk, 1998, Nelson and Lamb, 2000, Moser and Mattocks, 2000, Mattocks, 2000.