2. Production of Biogas by Anaerobic Digestion

Anaerobic digestion is a natural process in which bacteria convert organic materials into biogas. It occurs in marshes and wetlands, and in the digestive tract of ruminants. The bacteria are also active in landfills where they are the principal process degrading landfilled food wastes and other biomass. Biogas can be collected and used as a potential energy resource. The process occurs in an anaerobic (oxygen-free) environment through the activities of acid- and methane-forming bacteria that break down the organic material and produce methane (CH_4) and carbon dioxide (CO_2) in a gaseous form known as biogas.

Dairy manure waste consists of feed and water that has already passed through the anaerobic digestion process in the stomach of a cow, mixed with some waste feed and, possibly, flush water. The environmental advantages of using anaerobic digestion for dairy farm wastes include the reduction of odors, flies, and pathogens as well as decreasing greenhouse gas (GHG) and other undesirable air emissions. It also stabilizes the manure and reduces BOD. As large dairies become more common, the pollution potential of these operations, if not properly managed, also increases. The potential for the leaching of nitrates into groundwater, the potential release of nitrates and pathogens into surface waters, and the emission of odors from storage lagoons is significantly reduced with the use of anaerobic digestion. There may also be a reduction in the level of VOC emissions.

Elements of Anaerobic Digestion Systems

Anaerobic digester systems have been used for decades at municipal wastewater facilities, and more recently, have been used to process industrial and agricultural wastes (Burke, 2001). These systems are designed to optimize the growth of the methane-forming (*methanogenic*) bacteria that generate CH_4. Typically, using organic wastes as the major input, the systems produce biogas that contains 55% to 70% CH_4 and 30% to 45% CO_2. On dairy farms, the overall process includes the following:

- *Manure collection and handling*. Key considerations in the system design include the amount of water and inorganic solids that mix with manure during collection and handling, as described in Chapter 1.

- *Pretreatment*. Collected manure may undergo pretreatment prior to introduction in an anaerobic digester. Pretreatment—which may include screening, grit removal, mixing, and/or flow equalization—is used to adjust the manure or slurry water content to meet process requirements of the selected digestion technology. A concrete or metal collection/mix tank may be used to accumulate manure, process water and/or flush water. Proper design of a mix tank prior to the digester can limit the introduction of sand and rocks into the anaerobic digester itself. If the digestion processes requires a thick manure slurry, a mix tank serves a control point where water can be added to dry manure or dry manure can be added to dilute manure. If the digester is designed to handle manures mixed with flush and process water, the contents of the collection/mix tank can be pumped directly to a solids separator. A variety of solids separators, including static and shaking screens are available and currently used on farms.

- *Anaerobic digestion*. An anaerobic digester is an engineered containment vessel designed to exclude air and promote the growth of methane bacteria. The digester may be a tank, a covered lagoon (Figure 2-1), or a more complex design, such as a tank provided with internal baffles or with surfaces for attached bacterial growth. It may be designed to heat or mix the organic material. Manure characteristics and collection technique determine the type of anaerobic digestion technology used. Some technologies may include the removal of impurities such as hydrogen sulfide (H_2S), which is highly corrosive.

- *By-product recovery and effluent use*. It is possible to recover digested fiber from the effluent of some dairy manure digesters. This material can then be used for cattle bedding or sold as a soil amendment. Most of the *ruminant* and hog manure solids that pass through a separator will digest in a covered lagoon, leaving no valuable recoverable by-product.

- *Biogas recovery*. Biogas formed in the anaerobic digester bubbles to the surface and may accumulate beneath a fixed rigid top, a flexible inflatable top, or a floating cover, depending on the type of digester. (Digesters can also include integral low-pressure gas storage capability, as described in Chapter 4.) The collection system, typically plastic piping, then directs the biogas to gas handling subsystems.

- *Biogas handling*. Biogas is usually pumped or compressed to the operating pressure required by specific applications and then metered to the gas use equipment. Prior to this, biogas may be processed to remove moisture, H_2S, and CO_2, the main contaminants in dairy biogas, in which case the biogas becomes *biomethane* (see Chapter 3). (Partial removal of contaminants, particularly H_2S, will yield an intermediate product that we refer to in this report as *partially upgraded* biogas). Depending on applications, biogas may be stored either before or after processing, at low or high pressures (see Chapter 4).

- *Biogas use*. Recovered biogas can be used directly as fuel for heating or it can be combusted in an engine to generate electricity or flared. If the biogas is upgraded to biomethane, additional uses may be possible (see Chapter 5).

Anaerobic digestion is a complex process that involves two stages, as shown in the simplified schematic in Figure 2-2. In the first stage, decomposition is performed by fast-growing, acid-forming (*acidogenic*) bacteria. Protein, carbohydrate, cellulose, and hemicellulose in the manure are hydrolyzed and metabolized into mainly short-chain fatty acids—acetic, propionic, and butyric—along with CO_2 and hydrogen (H_2) gases. At this stage the decomposition products have noticeable, disagreeable, effusive odors from the organic acids, H_2S, and other metabolic products.

Figure 2-1 A dairy farm anaerobic digestion system (RCM, Inc., Berkeley, California)

In the second stage, most of the organic acids and all of the H_2 are metabolized by methanogenic bacteria, with the end result being production of a mixture of approximately 55% to 70% CH_4 and 30% to 45% CO_2, called biogas. The methanogenic bacteria are slower growing and more environmentally sensitive (to pH, air, and temperatures) than the acidogenic bacteria. Typically, the methanogenic bacteria require a narrow pH range (above 6), adequate time (typically more than 15 days), and temperatures at or above 70° F, to most effectively convert organic acids into biogas. The average amount of time manure remains in a digester is called the *hydraulic retention time*, defined as the digester volume divided by daily influent volume and expressed in days.

A more complete discussion of the anaerobic digestion process can be found in Appendix A.

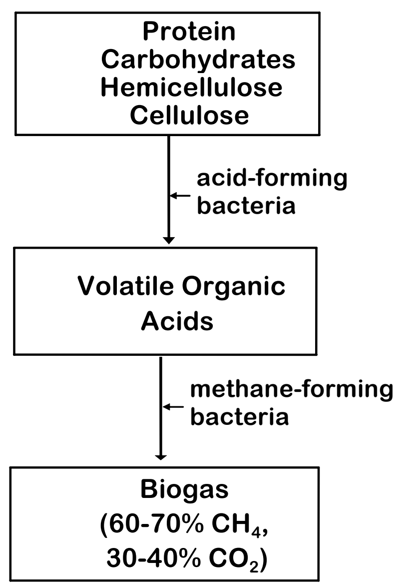

Figure 2-2 Simplified process of biogas production

Anaerobic Digestion Technologies Suitable for Dairy Manure

Numerous configurations of anaerobic digesters have been developed, but many are not likely to be commercially applicable for California dairy farms. This section briefly describes the three digester types most suitable for California dairies: ambient-temperature covered-lagoon, complete-mix, and plug-flow digesters. Table 2-1 provides the operating characteristics of these manure digester technologies. More detail about these technologies is provided in Appendix B.

Table 2-1 Characteristics of Anaerobic Digesters Suitable for On-Farm Use

Digester Type	Technology Level	Concentration of Influent Solids (%)	Allowable Solids Size	Supplemental Heat Needed?	HRT [a] (days)
Ambient-temperature covered lagoon	low	0.1 – 2	fine	no	40+
Complete mix	medium	2.0 – 10	coarse	yes	15+
Plug flow	low	11.0 – 13	coarse	yes	15+

[a] HRT = Hydraulic Retention Time = digester volume/daily influent volume

Ambient-Temperature Covered Lagoon

Properly designed anaerobic lagoons are used to produce biogas from dilute wastes with less than 2% total solids (98% moisture) such as flushed dairy manure, dairy parlor wash water, and flushed hog manure. The lagoons are not heated and the lagoon temperature and biogas production varies with ambient temperatures. Coarse solids such as hay and silage fibers in cow manure must be separated in a pretreatment step and kept out of the lagoon. If dairy solids are not separated, they float to the top and form a crust. The crust will thicken, which will result in reduced biogas production and, eventually, infilling of the lagoon with solids.

Unheated, unmixed anaerobic lagoons have been successfully fitted with floating covers for biogas recovery for dairy and hog waste in California. Other industrial and dairy covered lagoons are located across the southern USA in warm climates. Ambient temperature lagoons are not suitable for colder climates such as those encountered in New York or Wisconsin.

Complete-Mix Digester

Complete-mix digesters are the most flexible of all digesters as far as the variety of wastes that can be accommodated. Wastes with 2% to 10% solids are pumped into the digester and the digester contents are continuously or intermittently mixed to prevent separation. Complete-mix digesters are usually aboveground, heated, insulated round tanks. Mixing can be accomplished by gas recirculation, mechanical propellers, or circulation of liquid.

Plug-Flow Digester

Plug-flow digesters are used to digest thick wastes (11% to 13% solids) from ruminant animals. Coarse solids in ruminant manure form a viscous material and limit solids separation. If the waste is less than 10% solids, a plug-flow digester is not suitable. If the collected manure is too dry, water or a liquid organic waste such as cheese whey can be added.

Plug-flow digesters consist of unmixed, heated rectangular tanks that function by horizontally displacing old material with new material. The new material is usually pumped in, displacing an equal portion of old material, which is pushed out the other end of the digester.

Factors Influencing Anaerobic Digestion Efficiency

Digesters can function at ambient temperatures in warmer climates such as California, but with a lower biogas output than heated digesters. In some applications and in colder environments, digesters are heated. The optimal ranges for anaerobic digestion are between 125 to 135° F (*thermophilic* conditions) and between 95 to 105° F (*mesophilic* conditions). Anaerobic digestion under thermophilic conditions generates gas in a shorter amount of time than anaerobic digestion under mesophilic conditions. However, a higher percentage of the gross energy generated is required to maintain thermophilic conditions within the reactor. The extra heat is either extracted from the gross waste heat recovery in an engine or recovered from effluent.

Covered lagoons have seasonal variation in gas production due to the variation in ambient temperature. Gas production from complete-mix and plug-flow digesters are impacted less by ambient temperature variation since they are usually heated. On an annual basis, gas production from complete-mix and plug-flow digesters tends to be higher than for ambient-temperature covered lagoons because a higher percentage of solids entering complete-mix and plug-flow digesters is converted to biogas and the higher operating temperatures favor greater microbial activity. Gas production in all these digesters is dependent on hydraulic retention time.

Table 2-2 Modeled Comparison of Biogas Generation Potential of Three Different Anaerobic Digestion Processes on Typical 1,000-Cow Dairy Merced, CA Dairy [a]

Month	Biogas Generation (1,000 ft^3)		
	Covered Lagoon	**Plug Flow**	**Complete Mix**
January	949	1,713	1,713
February	1,096	1,547	1,547
March	1,358	1,713	1,713
April	1,383	1,658	1,658
May	1,488	1,713	1,713
June	1,544	1,658	1,658
July	1,648	1,713	1,713
August	1,634	1,713	1,713
September	1,532	1,658	1,658
October	1,475	1,713	1,713
November	1,323	1,658	1,658
December	1,003	1,713	1,713
Total Annual	16,430	20,172	20,172

[a] Modeled using US EPA AgStar Farmware program

A comparison of the biogas potential of the three main types of digesters for use on dairy farms was made by the US EPA (see AgStar website <http://www.epa.gov/agstar/>). The US EPA's Farmware program was run for a 1,000-milking-cow freestall dairy operated in Merced, California. The program was run under three different digester configurations: covered lagoon, plug flow, and complete mix. For the covered lagoon configuration, US EPA chose a manure management scheme in which all areas of the dairy were flushed and all dairy wastes ended up in the lagoon. To meet the higher total solids requirement of the plug-flow and the complete-mix designs, the chosen manure management option involved flushing the parlor area and scraping all other areas of the dairy. The results of biogas production in a typical year are shown in Table 2-2.

The results indicated that the plug-flow and the complete-mix digesters have the same gas production; however, the cost of a complete-mix digester is higher than a plug-flow system. A complete-mix digester must be larger than a plug-flow to accommodate the additional water added to reduce the total solids concentration of the influent. The gas output from the covered lagoon was significantly less than from the plug-flow and complete-mix digesters (especially in the winter months) because it was not heated and therefore had suboptimal conditions for gas production.

Environmental Impacts of Anaerobic Digestion

The environmental impacts of on-farm anaerobic digestion depend on the manure management system that the digester amends or replaces as well as the actual use of the biogas produced. Typically, the anaerobic digestion of dairy manure followed by flaring of biogas, combustion of biogas for electricity, or production and use of biomethane as fuel can provide a number of direct environmental benefits. These include:

- Reduced GHG emissions
- Potential reduction of VOC emissions
- Odor control
- Pathogen and weed seed control
- Improved water quality

One potentially negative environmental impact of anaerobic digesters that combust the biogas is the creation of nitrogen oxides (NO_x), which are regulated air pollutants and an ozone precursor. Nitrogen oxides are created by combustion of fuel with air. Combustion of dairy biogas or any other methane containing gas (whether in a flare, reciprocating or gas turbine engine, or a boiler) will emit NO_x. The emission rate varies but is generally lowest for properly engineered flares and highest for rich burn reciprocating (piston) engines. NO_x emissions are controlled by using lean burn engines, catalytic controls or microturbines. The latter two methods are fouled by the high sulfur content of biogas, and the H_2S must be scrubbed to prevent the swift corrosion of these devices.

Reduced Greenhouse Gas Emissions

The use of anaerobic digestion to create biogas from dairy manure can reduce GHG emissions in two distinct ways. First, when used in combination with a manure management system that stores manure under anaerobic conditions, it can prevent the release of CH_4, a greenhouse gas, into the atmosphere. Second, the biogas or biomethane generated by the anaerobic digestion process can replace the use of fossil fuels that generate GHGs.

The biogas generated from anaerobic digestion contains about 60% CH_4. It is this component, methane (which is also the main component of natural gas), that can produce energy. In addition to being an energy resource, however, CH_4 is also a GHG with 21 times the global warming potential, by weight, of CO_2. Globally, CH_4 constitutes 22% of anthropogenic GHG emissions in terms of carbon equivalents. In the USA, CH_4 contributes 10% of anthropogenic GHG emissions and 10% of the CH_4 is derived from animal manure (US DOE, 1999b, pp. 6, 13-14). Thus animal manure produces approximately 1% of all anthropogenic GHG emissions in the USA.

Most of the Central Valley dairies store manure in large lagoons under anaerobic conditions. Manure stored in anaerobic conditions produces the bulk of the GHG emissions from animal waste. The methanogenic bacteria that thrive in this environment produce CH_4, which is released into the atmosphere. If the lagoon is covered or the manure is digested in another type of digester, the CH_4 can be captured and combusted. This destroys the CH_4 and releases CO_2. Since each unit of CH_4 has 21 times the global warming potential of CO_2, 21 units of GHG are eliminated and 1 unit is created for each unit of CH_4 that is captured and combusted, creating an overall net gain of 20 units. This benefit will occur as long as the methane is combusted—whether the biogas is flared, used to generate electricity, or upgraded to biomethane and then combusted to produce energy. This benefit is in addition to the benefit when energy created by this renewable fuel replaces energy created by combusting a fossil fuel.

A good proportion of dairy manure in Southern California is stored aerobically. Methanogenic bacteria do not thrive in aerobic conditions and thus manure that is stored in corrals or piles where it is exposed to the air produces very little CH_4 (US EPA, 1999, p 7.4-15). Since manure stored in this manner releases little CH_4, putting it into an anaerobic digester produces no significant reduction in CH_4 emissions, although there may be some nitrous oxide (N_2O) reductions. Also, if the anaerobic digester has any significant leakage, emissions of CH_4 may actually be higher than they would be using aerobic (dry) storage alone.

Reduced Volatile Organic Compound Emissions

Volatile organic compounds, in combination with NO_x and sunlight, produce ozone, the primary element in smog and a criteria air pollutant. Thus VOCs are an ozone precursor and are regulated by State and federal law. In California, VOCs are often called reactive organic gases (ROG).

VOCs are an intermediate product generated by methanogenic bacteria during the transformation of manure into biogas. It is expected that the total volume of VOCs generated is related to the total volume of CH_4 produced, but the more effective the methanogenic decomposition, the lower the VOCs as a percentage of the biogas. VOCs are created by enteric fermentation (the digestion process of the cow) and released primarily through the breath of the cow. They are also produced by the anaerobic decomposition of manure. A well designed and managed anaerobic digester may reduce VOCs by more completely transforming them into CH_4. Some fraction of the remaining VOCs in the biogas should be eliminated through the combustion of the biogas.

For its emission inventory, the California Air Resources Board (CARB) uses an emission factor for dairy cows of 12.8 lb of VOCs per cow per year. (This emission factor is based on a single 1938 study, which measured CH_4 emissions from a cow but did not measure VOC emissions.) Based on this emission factor, dairies are a significant source of VOC emissions and a major contributor to ozone in the San Joaquin Valley. The CARB has not determined the portion of VOC emissions that is generated by manure-holding lagoons.

Current law, notably Senate Bill 700 (SB 700), requires California air districts to regulate dairies in accordance with the federal Clean Air Act. Since the San Joaquin Valley and the South Coast are extreme non-attainment areas for ozone (see <http://www.valleyair.org/General_info/faq_frame.htm>), major sources of pollution in those air districts need to control their VOC emissions. The San Joaquin Valley Air Pollution Control District has proposed that anaerobic digesters be required for new dairies that have more than 1,984 cows as a “best available control technology” (BACT) for ROGs (SJVAPCD, 2004). The South Coast Air Quality Management District (which covers the Los Angeles Basin) is reviewing the anaerobic digestion technology under its Proposed Rule 1127 (see <http://www.aqmd.gov/rules/reg/reg11/r1127.pdf>).

Now that dairies are being regulated for VOC emissions, air districts and other regulators recognize the importance of providing a better VOC emission factor. The CARB, the San Joaquin Air Pollution Control District, the US EPA Region IX, the US Department of Agriculture (USDA), and the State Water Board have initiated and funded several studies, mostly led by researchers from University of California Davis and California State University Fresno. The research is aimed at determining an emission factor for VOCs from California cows. Preliminary results indicate that most of the VOCs on the dairy come from enteric fermentation and from feed, with a smaller proportion from lagoons.

Increased Nitrogen Oxide Emissions

When biogas or any fuel is combusted in an internal combustion engine it produces NO_x, a criteria air pollutant as well as a precursor to ozone and smog.

For reciprocating engines the main NO_x production route is thermal, and is strongly temperature dependent. Internal combustion engines can produce a significant amount of NO_x. Maximum NO_x formation occurs when the fuel mixture is slightly lean, i.e. when there is not quite enough oxygen to burn all the fuel. Lean-burn engines typically have lower NO_x formation than stoichiometric or rich-burn engines because more air dilutes the combustion gases, keeping peak flame temperature lower. Gas turbines and microturbines also produce a very low level of NO_x because peak flame temperatures are low compared to reciprocating engines. A system to flare gas, if properly engineered, will generate a substantially lower level of NO_x than an uncontrolled reciprocating engine.

Dairy anaerobic digesters that burn biogas for electricity typically use reciprocating internal combustion engines; microturbines have not been used successfully because impurities in the biogas corrode the engines. When there is enough biogas to support a lean-burn engine, NO_x can be kept relatively low. The Inland Empire Utility Agency in Chino, California uses 700 to 1,400 kilowatt (kW) engines to combust biogas and has kept NO_x production below 50 ppm (Clifton, 2004), which meets BACT for waste gas as proposed by CARB in its guidance document to California air districts as required under SB 1298 (CARB, 2002, p.4). For smaller applications (capacity of less than 350 kW), there are no lean-burn waste-gas reciprocating engines available in the USA; consequently, NO_x formation at these facilities can be expected to be much higher.

There are several catalytic conversion technologies for reducing NO_x emissions which can be used on rich- and lean-burn engines that use natural gas, but the impurities in dairy biogas will substantially shorten the life of the catalytic NO_x controls. If the H_2S content of the biogas is reduced to a very low level before introduction to the engine, the emissions from the scrubbed dairy biogas will not degrade catalytic controls or microturbines as quickly. One California dairy has installed a H_2S scrubbing system and a catalytic emission control device on its engine. Initial tests are promising, but it is too soon to know if this will be a reliable solution. The current status of air district regulation of NO_x emissions will be discussed in Chapter 6.

If biogas is upgraded to biomethane, the selective catalytic reduction technologies used for natural gas engines can be used to keep NO_x formation at acceptable levels. Biomethane will not corrode microturbines and electricity generated in microturbines from biomethane has a very low accompanying NO_x formation.

Control of Unpleasant Odors

According to anecdotal reports, most of the approximately 100 anaerobic digesters processing animal manure in the USA were built to address odor complaints from neighbors. As more housing is built in formerly rural areas of California’s Central Valley, complaints about odors from dairies increase. Most of the odor problem comes from H_2S, VOC, and ammonia (NH_3-N) emissions from dairy manure. While hard to measure objectively, these odors are perceived as a serious environmental problem by residents in proximity to dairy farms. Fortunately, anaerobic digestion is a good method for controlling these odors, particularly if used in conjunction with a system that will scrub the H_2S from the biogas.

Control of Pathogens and Weed Seeds

Digesters that are heated to mesophilic and thermophilic levels are very effective in denaturing weed seeds and reducing pathogens. Pathogen reduction is greater than 99% in a 20-day hydraulic retention time, mesophilic digester. Thermophilic temperatures essentially result in the complete elimination of pathogens. Covered-lagoon digesters, which operate at ambient temperatures, have a more modest effect on weed seeds and pathogens.

Improved Water Quality

An anaerobic digester will have minimal effect on the total nutrient content of the digested manure. However, the chemical form of some of the nutrients will be changed. A digester decomposes organic materials, converting approximately half or more of the organic nitrogen (org-N) into NH_3-N. Some phosphorus (P) and potassium (K) are released into solution by decomposing material. A minimal amount of the P and K will settle as sludge in plug flow and complete mix digesters. However 30% to 40% of the P and K are retained in covered-lagoon digesters in the accumulated sludge. Dissolved and suspended nutrients are of lesser concern as they will flow through the digester.

The anaerobic digestion process is an effective way to reduce high BOD in the effluent. Biological oxygen demand is a measure of the amount of oxygen used by microorganisms in the biochemical oxidation of organic matter; BOD concentrations in dairy wastewater are often 25 to 40 times greater than those in domestic wastewater. Anaerobic processes can remove 70% to 90% of the BOD in high-strength wastewater at a lower cost, in terms of both land and energy inputs, than aerated systems.

Motivation for Realizing Environmental Benefits on Dairy Farms

Many of the environmental benefits discussed above also can be realized by capturing the biogas produced at a dairy and flaring it. In fact, flaring typically produces less NO_x than combustion of the biogas for generating electricity. Federal and state law require large landfills to flare their *landfill gas* (similar in composition to dairy biogas) to reduce VOC emissions and the danger of explosions. As a result of SB 700, the San Joaquin Air Pollution Control District proposed to require digesters as BACT for new or modified dairies with more than 1,954 head of cattle, although the proposal has since been withdrawn as a result of a lawsuit. At this time, the major motivations for smaller dairies to combust or capture/flare the CH_4 produced on-site are likely to be economic or as a means of odor control.

Whether used to generate electricity, or upgraded to biomethane and used for vehicular or engine fuel, biogas is a renewable energy product. Like other renewable energy sources, such as solar and wind-generated power, biogas can be substituted for greenhouse-gas-emitting fossil fuels, producing a net decrease in GHG emissions. On those dairy farms where manure is stored under anaerobic conditions (i.e., where it is not stored in piles that decompose aerobically over time), there is an added benefit. Using biogas as a fuel results in the reduction of CH_4 emissions that would otherwise be released into the atmosphere (e.g., through storage in uncovered lagoons).

However, without financial or regulatory motivations, farmers will have little motivation to capture and use dairy biogas.

Increasing the Methane Content of Biogas

There are several technologies that have been used to increase methane generation and extraction at landfills and wastewater treatment plants; conceivably, these techniques could also be applied to dairy wastes. Possible techniques include pretreatment of the feedstock with heat, ultrasonic devices, or impact grinding (all to increase the degree of hydrolysis of the feedstock); microbial stimulants; or co-digestion with other wastes.

Pretreatment Techniques

Thermal pretreatment can increase the CH_4 yield of certain substrates. However, it is not an effective pretreatment technique for the anaerobic digestion of all substrates. For example, Ferrer et al. found that thermal pretreatment at 80^{o} C (176^{o} F) did not enhance the anaerobic digestion of water hyacinth because water hyacinth's solubility increased only slightly under the tested conditions (2004, pp 2107-2109). In contrast, the pasteurization of slaughterhouse waste at the Upsalla biogas plant in Sweden resulted in a reported fourfold increase in CH_4 yields after thermal treatment at 70^{o} C (158^{o} F) for 1 hour (Norberg, 2004). However, the effects of this treatment method on high-lipid and protein waste have not been adequately studied to determine the reasons behind the increased methane production.

Ultrasonic pretreatment has been has been shown to be effective in disintegrating sewage sludge, resulting in greatly improved fermentation rates (Vera et al., 2004, pp 2127-2128). This method uses low-frequency ultrasound to induce cavitation with high shear forces, which promotes sludge disintegration. Short ultrasound bursts disperse sludge floc agglomerates without causing accompanying cell destruction. Longer ultrasound applications break down microorganism cell walls, causing intra-cellular material to be released to the liquid phase. The destruction of volatile solids increases according to the degree of cell disintegration. Increased biogas production was also observed. However, the application of this technology to manure solids is untried and its success uncertain due to the ligno-cellulosic character of manure.

Peltola et al. (2004, pp. 2,129 – 2,132) showed that impact grinding can increase the soluble *chemical oxygen demand* (COD) content of the organic fraction of municipal solid waste by approximately 2.5 times. This increased COD indicates partial disintegration of plant cells and microbial floc of the organic fraction of municipal solid waste. Though no increase in biogas production was observed, the onset of methane production began sooner as a result of impact grinding, and the digestion process was more stable than when the organic fraction of municipal solid waste was simply crushed. The breakdown of cell walls as a result of impact grinding could also improve the anaerobic digestion of dairy manure. However, any benefits that might be gained, such as an increased rate of biogas production and consequent reduction in hydraulic retention time and digester size, would need to be weighed against the increased energy (and resultant costs) required to grind the manure.

Microbial Stimulants

Aquasan® and Teresan® are *saponified* steroid products (available from Amit Chemicals in New Dehli, India) that are used to activate microbes. Both products are derived from plant extracts and work directly on the microbial population, restricting odor emissions by enzyme interference and accelerating digestion by stimulating the bacterial metabolism. In bench-scale experiments using Aquasan, a dosage level of 15 ppm was optimum for gas production, and resulted in production that was 55% higher than that from untreated cattle manure. In another bench-scale study, the addition of Teresan to the mixed residues of cattle manure and kitchen wastes at a concentration of 10 ppm produced 34.8% more gas than the uninoculated mixture **(**Singh et al., 2001, pp. 313-316). The efficacy of these microbial stimulants has not been demonstrated at the commercial scale.

Co-Digestion with Other Waste Sources

Co-digestion of manure with other substrates such as industrial wastes, grass clippings, food industry wastes, animal by-products (slaughterhouse waste), or sewage sludge can result in multiple benefits. This includes an improved nutrient balance of total organic carbon, nitrogen, and phosphorous, which results in a stable and maintainable digestion process and good fertilizer quality (Braun and Wellinger, 2003). Co-digestion also improves the flow qualities of the co-digested substrates. In addition, the economics of digester projects benefit from the increased gas production due to co-digestion and also from the income generated from tipping fees (i.e., waste disposal fees that are generally based on a per volume or weight basis).

Increased biogas production from the co-digestion of dairy manure and grease-trap waste has been documented at the Amersfoort wastewater treatment plant in the Netherlands (Mulder et al., 2004, pp. 2,064-2,068). The results at Amersfoort showed that the grease-trap waste was converted with an efficiency of 70% at a hydraulic retention time of 20 days. The biogas production rate was doubled from approximately 180,000 ft^3/d using sewage sludge alone to approximately 353,000 to 424,000 ft^3/d when co-digested with grease-trap waste.

As previously noted, the typical dairy farm biogas contains approximately 55% to 70% CH_4 and approximately 30% to 45% CO_2. The theoretical CH_4 to CO_2 ratios of various substrates were determined by Jewel et al. (1978) using the following equation, developed by McCarty (1964):

$$C_nH_aO_b + (n - a/4 - b/2)\ H_2O \rightarrow (n/2 - a/8 + b/4)\ CO_2 + (n/2 + a/8 - b/4)\ CH_4 \qquad (1)$$

The theoretical CH_4 content of biogas for various substrates, based on this equation, are presented in Table 2-2. More detail about the stoichiometry of the anaerobic digestion process of various substrates can be found in Appendix A.

Table 2-3 Theoretical Methane Content of Biogas

Substrate	Chemical Composition	Methane, % of Total Gas
Fat	$C_{15}H_{31}COOH$	72
Protein	C_4H_6ON	63
Carbohydrate	$C_6H_{12}O_6$	50

Readily degradable substrates (urea, fats, and proteins) yield the highest percentages of CH_4. However, the fats and proteins available from industrial wastes such as slaughterhouse and rendering operations may, in high concentrations, inhibit the anaerobic digestion process through the accumulation of volatile fatty acids and long chain fatty acids (Salminen et al., 2003; Broughton et al., 1998). When manure is added to the anaerobic digestion process, it acts as a buffer and provides the essential nutrients necessary for digestion, overcoming some of the operational problems associated with the anaerobic digestion of lipids and proteins. A tour of Swedish biogas plants taken by the authors of this report tends to support these conclusions (WestStart/CalStart, 2004). Table 2-3 presents the operational parameters for three of the Swedish biogas plants that were visited during this tour.

As seen in Table 2-3, large quantities of biogas with high CH_4 content can be produced from manure mixed with slaughterhouse and food processing waste; however, this level of production comes with certain operational restrictions. For example, at the Laholm plant, no more than 40% slaughterhouse waste is used in the process. When a higher percentage of slaughterhouse waste is included, yeasts are produced and the reactor must be evacuated for the process to be recovered. The Linkoping plant uses the highest percentage of slaughterhouse waste of the three plants. This plant monitors incoming loads for volatile fatty acids, alkalinity, and dry matter content and also monitors the reactor for these same parameters two to three times a week. If the digesters begin to foam as result of high volatile fatty acid content, manure is added to stabilize the process. The plant uses bench-scale fermenters to test new wastes. Thus, the Linkoping plant successfully uses a high percentage of slaughterhouse waste to produce high-methane biogas, as long as it maintains a high degree of process monitoring and control.

Table 2-4 Operational Parameters for Three Swedish Biogas Plants

Operational Parameter	Laholm Plant	Boras Plant	Linkoping Plant
Waste mass processed (tons/day)	14	82	148
Total solids content (%)	10	30	10 – 14
Waste composition	33% pig manure 27% dairy manure 40% slaughterhouse & potato peels	restaurant food & grease trap household food food processing slaughterhouse	75% slaughterhouse 15% food processing & pharmaceutical 10% manure
Biogas production (ft^3/hour)	~18,000	~14,000	~48,000
Biogas quality (% methane)	75	No data	70-74
Feedstock processing	slaughterhouse waste minced to ~0.5 inch	Muffin Monster® [a] (30% to 8% total solids)	slaughterhouse waste minced to ~0.5 inch
Reactors [b]	2	1	2
Operating temperature	95° F (mesophilic)	~130° F(thermophilic)	100° F (mesophilic)
HRT	21 days	16 – 17 days	30 days
Pasteurization	~160° F for 1 hour	~160° F for 1 hour	~160° F for 1 hour
Process heat	10% of the biogas	10% – 15% of the biogas	-

[a] Muffin Monster is the registered trademark of JWC Environmental for grinding machines that reduce particle size of feedstock.

[b] Continuously-stirred tank reactors

Because of the limited degree of monitoring and process control available at dairy farms, the percentage of slaughterhouse waste would likely need to be limited to less than 33% by volume of the incoming waste stream to prevent yeasting or foaming problems. In addition, it would be appropriate to digest slaughterhouse and other food processing waste in a complete-mix digester, which gives a higher degree of control over the digestion process than do plug-flow and covered-lagoon digesters.

Effluent Absorption of Carbon Dioxide

The chemistry of the anaerobic digestion process indicates that the CH_4 content of anaerobic digesters is typically 55% to 65% and cannot be much higher than 70%, even if the substrate is all fats and vegetable oils (see Appendix A for a detailed analysis). However, some standard anaerobic digesters have produced biogas with a CH_4 content higher than would be expected based on the anaerobic digestion process alone.

Biogas methane contents of 65% to 80% appear to be the result of absorption of excess CO_2 in the digester effluent. Higher CH_4 content than this is not likely, as it is not possible for digester effluents to absorb the additional CO_2 that would be needed to produce higher methane biogas. In a few cases, such as when biogas has been collected from partially covered ponds, CH_4 contents as high as 90% have been observed, the result of absorption of CO_2 by the effluent, which is of limited capacity. Other anaerobic digestion processes, such as “two-phase” digestion, might produce marginal increases in CH_4 content, but these processes are not suitable for dairy wastes (and have limited success in other applications, as explained in Appendix A).

Centralized Digestion of Dairy Wastes for Biogas Production

Although many California dairies are following the trend towards increased animal numbers per dairy, about half of the state’s dairy animals remain in smaller herds. The smaller dairies, mostly unable to afford individual manure digestion systems, may be able to cooperate with similar local enterprises to build and operate “community manure digestion facilities.” Tanker trucks could be used to transport manure from various farms to a central treatment facility. Facility output could be returned to contributing farms or otherwise distributed in a controlled, regulated fashion. Such centralized treatment facilities are conceptually the same as large on-farm production facilities, with the addition of load-out points for tank truck pickup and discharge. Also, centralized facilities are likely to be larger than most on-farm digestion facilities.

Another option, especially when the local number of dairy cows is not sufficient to make centralized processing economically viable, is to seek other organic wastes for inclusion in the centralized system. Co-digestion of animal manures with food processing wastes in community digestion facilities is practiced in Denmark (University of Southern Denmark, 2000) and other European locations, and could be applicable also in some dairy areas in California. In particular, the addition of food processing wastes to manure could improve system economics, by providing waste-tipping fee revenues while generating more biogas.

Food-processing industries typically dispose of their waste streams through on-site aerobic treatment, discharge into sewer systems, sending solids to landfills, or regulated land application, all of which are relatively expensive. Recipients of these waste streams are required to meet local, state, and federal standards. Because food wastes are typically high in volatile solids concentration, they may produce significant odor when treated through land application. Food waste requires high energy inputs to process at a sewage treatment plant, where it can cause substantial sludge production, as well as requiring increased sewage treatment plant capacity.

Centralized Digesters and Gas Production

Centralized digesters have no intrinsic advantage with regard to gas production per unit volume as compared to on-farm digesters, but they will realize some *economies of scale* as the cost of anaerobic digestion per animal unit will decrease with herd size. However, trucking costs will reduce any economies realized. The main criterion with regard to gas production for both centralized and decentralized digesters is the age of the manure that reaches the digester. Ideally, collection should occur frequently enough that the manure used in digestion is no more than 3 days old. As manure ages it loses volatile solids, reducing the gas production potential. After about 30 days, manure biogas yield is very low.

Transport of Manure and Digested Effluent to Centralized Digesters

A major consideration for centralized digestion is the practicality of transportation. Manure must be transported from the various farms to the community or regional digester. After digestion, the digested liquid is transported back for field application, while the digested solids are typically composted and sold at the central digester location.

To understand how the transportation process might affect the viability of a centralized digester, we contacted Zwald Transport. They perform “two-way” hauling for the Port of Tillamook Bay regional digester. Mr. Zwald reported that the speed of loading and unloading is the key to success, and the best equipment to ensure this speed is a vacuum tanker. The process is also tightly controlled by the transporter: all of Zwald’s pick-up and delivery operations are under control of the driver and the farmer provides only the hose to the truck and pipe to the storage lagoon. The farmer is not required to buy a pump or valves or to modify any existing pumping system (Zwald, personal communication, November 2003).

Zwald’s truck is a 5,500-gallon vacuum tanker in a semi-trailer (combination) configuration. Larger units are possible, but the trade-off is maneuverability. A full load of digested liquid is taken on in 3 minutes, 30 seconds. Farm manure takes longer to load. There is some time variation due to the different loading situations, but the average time to load manure is around 7 minutes. The farm hoses (purchased by the farmers) are always ready to hook up to the truck. A suction hose is carried on the truck, but is used in emergencies only. Total turnaround time for a farm that is 2 miles from the digester site is about 55 minutes. One farm, 9 miles from the digester, has a total turnaround time of an hour and 35 minutes.

Another example of transportation services for an ongoing centralized digester is DeJaeger Trucking, which collects and hauls manure to the Inland Empire Utility Agency digester in Chino, California. DeJaeger uses a Honey Vac (a vacuum tanker truck) to collect the manure from the feed aprons, which have concrete floors. The manure contains 12% to 16% solids and the truck holds 25 tons. DeJaeger’s hauling rate is $45 per hour, and the furthest effective haul is about 5 miles. The cost of hauling is about $4/ton (DeJaeger, 2004).

These two examples illustrate the importance of distance, time, and other details that affect the viability of a centralized digester. Two general principles that should be adhered to when considering the start-up of a community digester include the following:

- Maximum haul distance to a centralized digester should be no more than 5 miles. A general rule of thumb is that manure from the equivalent of 6,000 mature Holstein cows must be available in a 5-mile radius of the centralized facility.
- Operational details such as collection, hauling, distribution, and costs must be carefully negotiated through contracts and maintained through active cooperation and management among participants.

Pumping manure through a pipeline is an alternative to trucking. However, this requires a higher moisture content in the manure, a suitable piping infrastructure, and pumping facilities. It is equivalent to building a sewage system for the manure.