Chapter 9

ANAEROBIC DIGESTION

Chapter 9.– ANAEROBIC DIGESTION

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ANAEROBIC DIGESTION

Introduction

Anaerobic ("without air") digestion is the process that occurs when various kinds of bacteria consume plant or animal material in an airtight container called a digester. Temperatures between 950 and **140°F favor bacteria that release biogas (50 to 70 percent methane — essentially natural gas — with most of the remainder as carbon dioxide — CO_2). The bacteria may be present** in the original material when charged (as is the case with cattle manure) or may be placed in the digester when it is initially charged. The gas has the heat value of its methane component, 500 to 700 Btu/stdft[3], and can be used directly as a heat fuel or in internal combustion engines. I n some cases there is enough hydrogen sulfide (H_2S) present to cause corrosion problems, particularly in engines. H_2S can be removed by a simple, inexpensive, existing technology. CO_2 can be removed by a somewhat more complex and expensive technology, which would need to be employed if the gas is to be fed into a natural gas pipeline.

The anaerobic digestion process is especially well adapted to slurry-type wastes and has environmental benefits in the form of treating wastes to reduce pollution hazards and to reduce odor nuisances. Furthermore, the residual from the process can be returned to land, either directly or through animal refeeding technologies, and thus retain nitrogen and organic levels of soil. Most other biomass energy conversion processes more nearly totally destroy the input material.

Generic Aspects of Anaerobic Digestion

The anaerobic digestion **process involves a number of different bacteria and a digester's performance depends on a large number of variables. The basic process is considered first and then the feedstocks and byproducts of the process.**

Basic Process

Not all of the bacteria involved in anaerobic digestion have been identified and the exact biochemical processes are not fully understood. Basically, however, the process consists of three steps: [2] 1) decomposition (hydrolysis) of the plant or animal matter to break it down to usable-sized molecules such as sugar, 2) conversion of the decomposed matter to organic acids, and 3) conversion of the acids to methane. Accomplishing these steps involves at least two different types of bacteria.

The rate at which the biogas forms will depend on the temperature (higher temperature usually gives a faster rate) and the nature of the substrate to be digested. Cellulosic materials, such as crop residues and municipal solid waste, produce biogas more slowly than sewage sludge and animal manure. Disturbances of the digester system, changes in temperature, feedstock composition, toxins, etc., can lead to a buildup of acids that inhibit the methane-producing bacteria. Generally, anaerobic digestion systems work best when a constant temperature and a uniform feedstock are maintained.

When a digester is started, the bacterial composition is seldom at the optimum. **But if the feedstock and operating conditions are held constant a process of natural selection**

[1] J J Wolis, *American Journal 01 Clinical Nutrition, 27 (11),* p 1120, 1974

[2] E C Clausen and J L Gaddy, "Stagewise **Fermentation of** Biomass **to Methane," Department of** Chemical Engineering, University of Missouri, Rolla, Mo , 1977

takes place until the bacteria best able to metabolize the feedstock (and thus grow) dominate. Biogas production begins within a day or so, but complete stabilization sometimes takes months.

Numerous sources for good anaerobic bacteria have been tried, though the process is basically one of hit and miss. The potential for improvement cannot be assessed at this time. Future developments could produce superior genetic strains of bacteria, but too little is known about the process to judge if or when this can be accomplished. It is quite possible that if such strains are to be effective, the input material may first require pasteurization.

Biogas yields vary considerably with feedstock and operating conditions. Operating a digester at high temperatures usually increases the rate at which the biogas is formed, but raising the temperature can actually decrease the net fuel yield as more energy is required to heat the digester. The optimum conditions for biogas yields have to be determined separately for each feedstock or combination of feedstocks.

Feedstocks

A wide range of plant and animal matter can be anaerobically digested. Both the gas yields and rates of digestion vary, Generally materials that are higher in lignin (e. g., wood and crop residues[3]) are poor feedstocks because the lignin protects the cellulose from bacterial attack. Pretreatment could increase their susceptibility to digestion. ' However, even then digestion energy efficiencies generally do not exceed 50 to 75 percent. Thus, more usable energy can generally be obtained through combustion or thermal gasification of these feedstocks (see ch. 5).

The best feedstocks for anaerobic digestion usually are wet biomass such as fresh animal manure, various aquatic plants, and wet food-processing wastes such as those that occur in the cheese, potato, tomato, and fruit-processing industries. See table 56 for a summary of the suitability of various feedstocks for digestion.

Byproducts

The digester effluent contains bacteria as well as most of the undigested material in the feedstock (mostly lignocellulose) and the solubilized nutrients. The process has the potential for killing most disease-causing bacteria, but volatile losses of ammonia may increase with anaerobic digestion. [5]

The most generally accepted technology for disposal of the effluent is to use it as a soil conditioner (low-grade fertilizer). Animal manure is already used widely for this but there is some controversy over whether the digester effluent is a better source of nitrogen than the undigested manure. * The actual added value (if any) as a fertilizer, however, will have to be determined experimentally and is likely to be highly feedstock specific. The effluent may also be used as fertilizer for aquatic plant systems. In one case the effluent is dewatered and used as animal bedding in place of sawdust. [6]

Another potential use of the effluent is as an animal feed. It has been claimed that the protein mix in the cake obtained from dewatering the effluent is superior to that of undigested manure.[7] Biogas of Colorado has concluded a successful animal feeding trial of digester cake and Hamilton Standard has also done feeding trials.[8]

[3]See also, J T Pfeffer, "131010 ogical Conversion of Crop Residues to Methane, " in *Proceedings of the Second A nnual Symposiurn on Fuels for Biomass*, Troy, N Y , June 20-22, 1978

[4]P L McCarty, et al , "Heat Treatment of Biomass for Increasing Biodegradability, " in *Proceedings of the Third Annual Biomass Energy Systems Conference*, sponsored by the Solar Energy Research Institute, Golden, Colo , June 1979, TP-33-285

[5]J A. Moore, et al , "Ammonia Volatilization From Animal Manures, " in *Biomass Utilization in Minnesota*, Perry Black shear, ed , National Technical Information Service

● The nitrogen is more concentrated in the effluent, but it is also more volatile

[6]John Mart[n, Scheaffer and Roland, Inc , Chicago, Ill, private communication, 1980

[7]B G Hashimoto, et al , "Thermophillic Anaerobic Fermentation of Beef Cattle Residues, " in Symposium *on Energy From Biomass and Wastes*, Institute of Gas Technology, Washington, D C , Aug 14-18, 1978

[8]D J Lizdas, et al , "Methane Generation From Cattle Residues at a Dirt Feedlot, " DOE report COO-2952-20, September 1979

Table 56.-Suitability of Various Substrates for Anaerobic Digestion

Feedstock	Availability	Suitability for digestion	Special problems
Animal wastes			
Dairy	Small- to medium-sized farms, 30-150 head	Excellent	No major problems, some systems operating.
Beef cattle ., ., .,	Feedlots, up to 1,000-100,000 cattle	Excellent	Rocks and grit in the feed require degritting, some systems operating.
Swine	100-1,000 per farm	Excellent	Lincomycin in the swine feed will inhibit digestion–full-scale systems on university farms.
Chicken	10,000-1,000,000 per farm	Excellent	Degritting necessary, broiler operations need special design due to aged manure, tendency to sour.
Turkey.	30,000-500,000 per farm	Excellent	Bedding can be a problem, manure is generally aged, no commercial systems operating.
Municipal wastes			
Sewage sludge	All towns and cities	Excellent	Vast experience.
Solid wastes	All towns and cities	Better suited to direct combustion	Designed landfill best option
Crop residues			
Wheat straw . .	Same cropland	Poor, better suited to direct combustion	Particle size reduction necessary, low digestibility, no commercial systems.
Corn stover.	Same cropland	Poor, better suited to direct combustion	No commercial systems, no data available, particle size reduction necessary.
Grasses			
Kentucky blue.	Individual home lawns	Very good	Distribution of feedstock disperse, no commercial systems.
Orchard grass.	Midwest	Fair	No commercial systems, no data on sustainability of yields.
Aquatic plants			
Water hyacinth	Southern climates, very high reproduction rates	Very good	No commercial operations, needs pregrinding.
Algae. . . . . .,. . . .	Warm or controlled climates	Good	Longer reaction time than for animal wastes.
Ocean kelp	West coast, Pacific Ocean, large-scale kelp farms	Very good	Full-scale operations not proven, no present value for effluent.
Various woods. . . .	Total United States	Poor, better for direct combustion or pyrolysis	Will not digest.
Kraft paper.	Limited	Excellent, need to evaluate recycle potential and other conversion processes	Premixing watering necessary.

SOURCE Tom Abeles and David Ellsworth, "Blologlcal Production of Gas, contractor report to OTA by I E Associates, Inc., Minneapolis, Minn. , 1979

Although most of the disease-causing bacteria are killed by digestion of the manure, several questions about refeeding of digester effluents need to be resolved. Buildup of toxic materials, development of resistance to antibiotics by organisms in the cake, permissible quantities of cake in the diet, storage, and product quality are all issues that have been raised. There is no firm evidence that these will present significant problems, however.

To avoid some of these problems, the Food and Drug Administration has generally favored cross-species feeding, but has not sanctioned its use as a feed or feed ingredient.[9] The use of digester effluents as an animal feed, however, would greatly improve the economics of manure digestion. Consequently, the value, use, and restrictions on using digester effluents as animal feeds should be thoroughly investigated. Moreover, the animal feed value of effluents from the digestion of feedstocks other than manure should also be investigated.

[9] T P Abeles, "Design and Engineering Considerations in Plug Flow Farm Digesters, " in Symposium on *C/can Fuels From Biomass,* Institute of Gas Technology, 1977

Reactor Types

There are numerous possible designs for anaerobic digesters, depending on the feedstock, the availability of cheap labor, and the purpose of the digestion. The most complex and expensive systems are for municipal sewage sludge digestion, but the primary purpose of these has been to stabilize the sludge and not to produce biogas.

Digester processes have been classified into three types, depending on the operating temperature: 1) psychrophilic (under 680 F), 2) mesophilic (680 to 1130 F), and 3) thermophilic (11 30 to 150° F). The cost, complexity, and energy use of the systems increase with the temperature, as does the rate of gas production. The amount of gas produced per pound of feedstock, however, can either increase or decrease with temperature. Retention time is also an important consideration, wherein maximum gas production per pound of feedstock is sacrificed for reduced size and cost of the digester. Anaerobic digesters in the mesophilic and thermophilic ranges have used agricultural wastes, residues, and grasses, to produce biogas. The optimum temperature appears to be both site and feedstock specific. There are still unresolved technical questions about the tradeoffs between mesophilic and thermophilic digesters, but most onfarm systems have been mesophilic.

Other design parameters include continuous versus batch processes, mixed versus unmixed reactors, and other features. Some of the major types are summarized in table 57 and discussed briefly.

Single-Tank Plug Flow

This system is the simplest adaptation of Asian anaerobic digester technology (figures 28-30). The feedstock is pumped or allowed to flow into one end of a digester tank and removed at the other. Biogas is drawn off from the top of the digester tank. The feed rate is chosen to maintain the proper residence time* in the digester and the feed or digester contents can be heated as needed. Depending on the placement of the heating pipes, some convective mixing can also occur.

● The time the feedstock remains in the digester

Multitank Batch System

This system consists of a series of tanks or chambers which are filled sequentially with biomass and sealed. As each unit completes the digestion process, it is emptied and recharged. This type of reactor is best suited to operations where the feedstock arrives in batches, for example, grass or crop residues that are collected only at certain times of the year or turkey or broiler operations that are cleaned only when the flocks are changed. This digester system, however, is relatively labor intensive.

Single-Tank Complete Mix

The single-tank complete mix system (figure 31) has a single rigid digester tank which is heated and mixed several times a day. It has been argued that mixing enhances the contact of bacteria with the feedstock and inhibits scum formation, which can interfere with digester operation. Theoretical calculations, '" however, indicate that the mixing does not improve bacterial contact, and these calculations have been confirmed experimentally in one case. Single-tank complete-mixed digesters are used to treat municipal sewage sludge and have been used in the larger anaerobic digester systems (exclusive of landfills).

Anaerobic Contact

The single-tank complete-mix system effluent can be transferred to a second unmixed

'('P C Augenstein, "Technical Principles of Anaerobic Digestion, " Dynatech R&D Co, presented at course *Biotechnology for Utilization of organic Wastes,* Universidad Autonoma Metropolitana, Iztapalapa, Mexico, 1978

''K D Smith, et al , "Design and First Year Operation of a 50,000 Gallon Anaerobic Digester at the State Honor Farm Dairy, Monroe, Washington, " Department of Energy contract EG-77-C-06-1016, ECOTOPE Group, Seattle, Wash , 1978

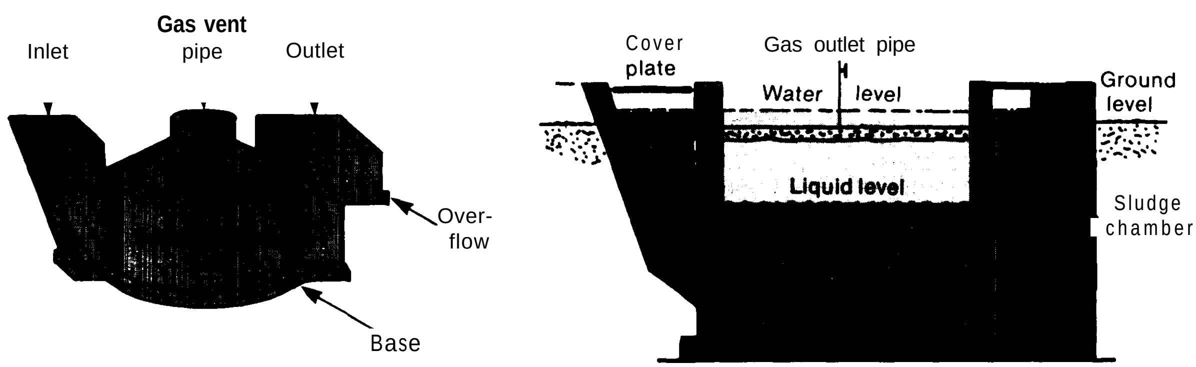
Table 57.–Anaerobic Digester Systems

Type of system	Application and inputs	Scale[a]	Stage of development	Advantages	Disadvantages
Landfill	Existing and planned landfills municipal solid wastes, sewage sludge, warm climates	2×10^6 tons of waste and up (28-acre landfill)	Commercial for "as is landfills, controlled land filling in pilot stages	Low cost, tanks not required, high loading rates possible, no moving parts	Gas generation may last only 10 years in "as is" landfills, gas usage onsite may present problems
Single-tank plug flow	All types of organics, farm and feedlot operations	Small to large	Commercial	Low cost, simple design can run high solids wastes, can have gravity feed and discharge	Low solids wastes may stratify
Multitank batch system	Can accept all types of wastes, limited application crop residues, grasses, chicken broilers, turkeys	Small to large	Commercial, in Asia	Simple, low maintenance, low cost, complete digestion of materials	Gas generation not continuous, labor-intensive feed and discharge, low gas production per day
Single-tank complete mix	All types of organics sewage treatment, farm and feedlot, municipal solid wastes	Small to large	Commercial	Proven reliability, works well on all types of wastes	Greater input energy to run mixers, higher cost than plug flow
Anaerobic contact	Sewage sludge and other organics, limited application (see variable feed)	Medium to large	Commercial, for sewage treatment	Smaller tank sizes, operation not overly critical	Two tanks necessary
Two or three phase	Cellulosic feedstocks	Medium to large	Pilot scale	Allows more complete decomposition, greater gas yields, greater loading rates, lower retention times	Feed rates vary with feedstocks, have not been attempted full scale, require tight controls and management of the operation
Packed bed	Dilute organics–sewage, food-processing wastes, very dilute animal wastes—Industrial and commercial	Medium to large	Commercial, as waste treatment technology	High loading rates possible, short retention times	Tends to clog with organic particles, limited to dilute wastes
Expanded bed	Dilute organics-sewage, food-processing wastes, very dilute animal wastes	Undetermined	Laboratory	High loading rates, low temperature digestion, high quality gas, short retention times	Not developed, high energy input to operate pumps, no operating data
Mixed bed	Sewage sludge, animal wastes, food-processing wastes–fairly dilute mixtures	Small to large	Pilot scale	Fast throughput, high loading rates, higher solids input than packed beds	Tends to clog, high pumping energy input no operating data
Variable feed	All types of organics, farms and feedlots	Small to medium	Conceptual–combines plug flow with anaerobic contact	Allows seasonal peaking of gas production, preserves nutrient value of material, low cost	Feed-discharge may require extra pump

[a]Scale defined as small—0 to 30,000 gal medium—30 000 to 80000 gal, and large—over 80,000 gal

SOURCE Tom Abeles and David Ellsworth Biological Production of Gas " contractor report to OTA by I E Associates Inc Minneapolis, Minn 1979

Figure 28.—Chinese Design of a Biogas Plant



SOURCE: K. C. Khandeleval, "Dome-Shaped Biogas Plan," Compost *Science,* March/April 1978.

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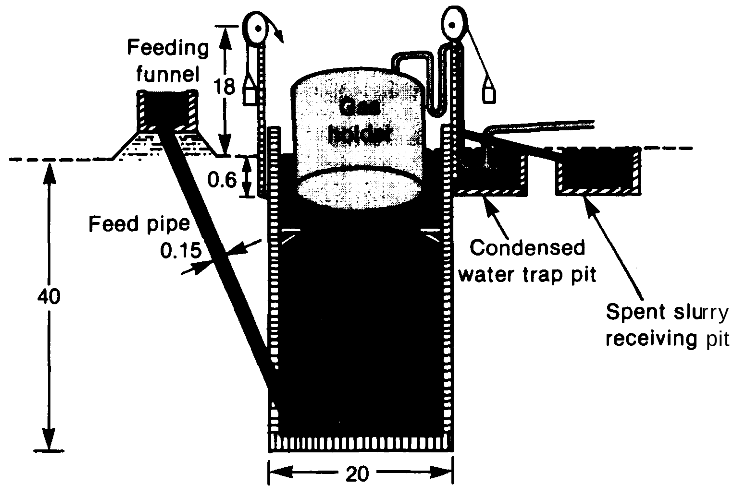
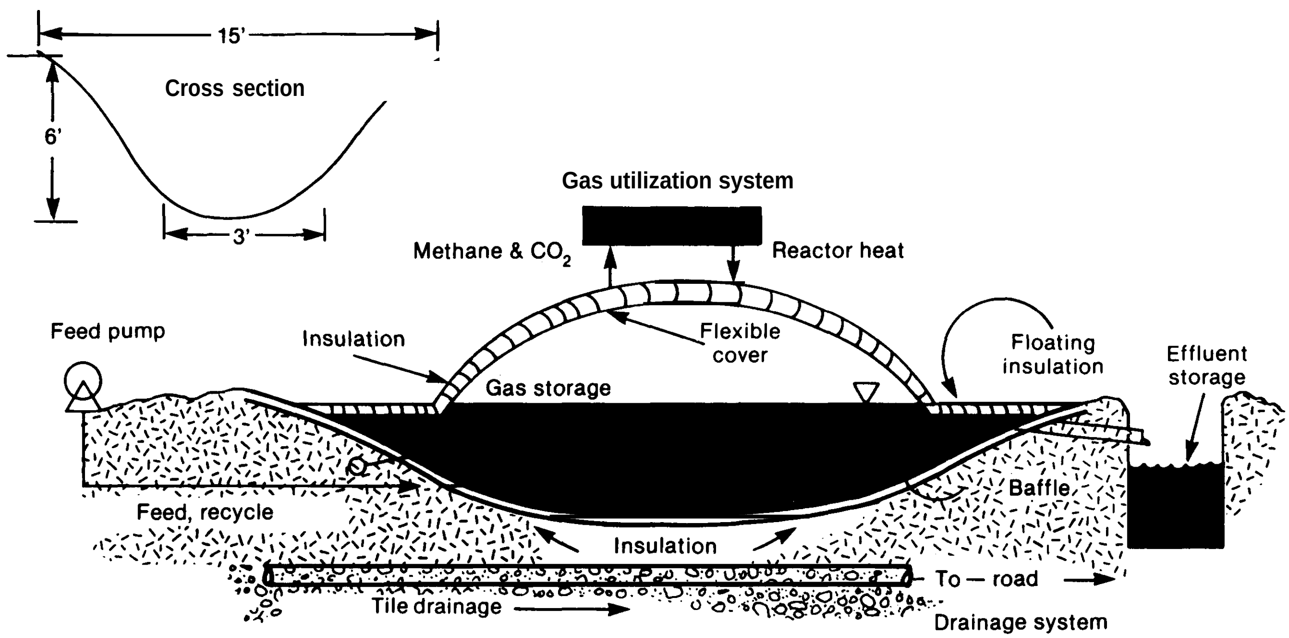
Figure 29.—Diagram of a Gobar Gas Plant (Indian)



All dimensions in meters

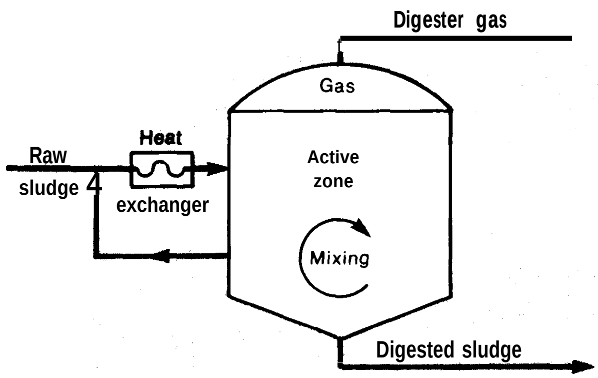
SOURCE: R. B. Singh, "Biogas Plant," Gobar Gas Research Station, Ajitmal, Etaweh (V.P.), India, 1971

Figure 30.-Plug Flow Digestion System



SOURCE: W. J. Jewell, et al., "Low Cost Methane Generation on Small Farms," presented at Third Annual Symposium on Biomass Energy Systems, Solar Energy Research Institute, Golden, Colo., June 1979

Figure 31. —Single-Tank Complete Mixed Digester



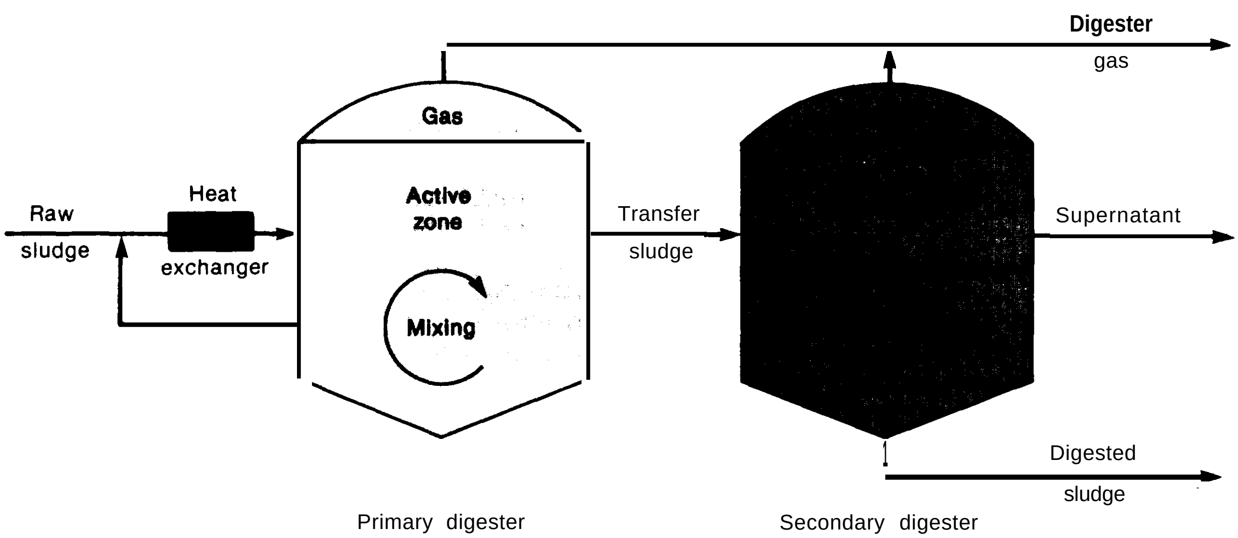
SOURCE Environmental Protection Agency, "Process Design Manual, Sludge Treatment and Disposal," EPA 625/1-29-001, September 1979

and unheated storage tank. Here the biomass undergoes further digestion and solids settle out (figure **32).** In other words, by adding a second, inexpensive digester tank gas **yields can be improved. These** systems have been **used extensively in sewage treatment and may re-** ceive wide application where preservation of the effluents nutrient value requires covered lagoons or in short throughput systems located in warm climates.

Two or Three Phase

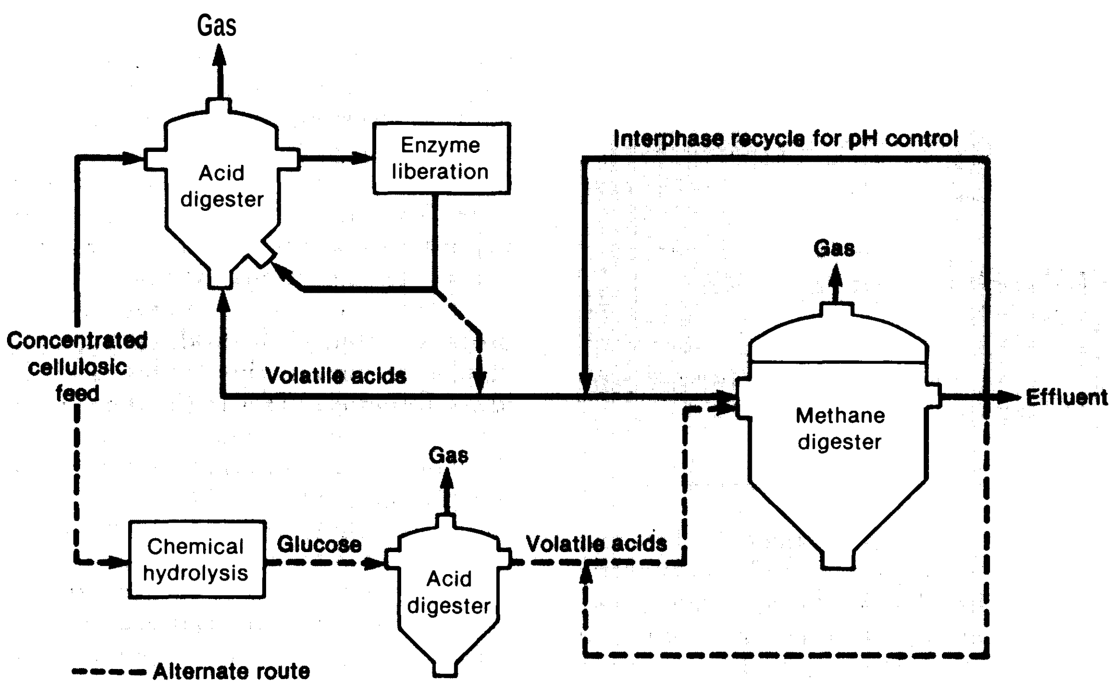
As mentioned previously under "Generic Aspects of Anaerobic Digestion, " the basic process consists of a series of biochemical steps involving different bacteria. The idea behind the multitank systems is to have a series of digester tanks (figure 33) each of which is separately optimized for one of the successive digestion steps. The rationale behind such system is the hypothesis that they: 1) can accept higher feedstock concentrations without inhibiting the reactions in successive stages, 2) have greater process stability, 3) produce higher methane concentrations in the biogas, and 4) require lower retention times in the digester than with most single-phase digesters. The majority of the work on this approach has been on municipal sewage sludge, although the Institute for Gas Technology hopes to eventually transfer the technique to kelp digestion. The need for uniform feed rates and controls may limit the use of two or multiphased systems to larger or extremely well-managed operations; but this type of reactor should be carefully examined for other anaerobic digestion applications because of its potentially high efficiencies.

Figure 32.—Two-Stage Digester



SOURCE Environmental Protect Ion Agency, "Process Design Manual, Sludge Treatment and Disposal," EPA 625/29-001, September 1979

Figure 33.—Two-Phase Digestion of Cellulosic Feed



SOURCE S Ghos and D. L Klass, "Two Phase Anaerobic Digestion," *Symposium on Clean Fuels from Biomass* (Institute of Gas Technology, 1977)

Packed Bed (Anaerobic Filter)

In this system a dilute stream of feedstock is fed up through a verticle column packed with small stones, plastic balls, ceramic chips, or other inert materials (figure 34). Because the bacteria attach themselves to the inert material, it is possible to pass large quantities of feedstock through it while maintaining a high bacterial concentration in the digester. The system is best suited to municipal sewage (and other dilute feedstocks). More concentrated feedstocks tend to clog the column.

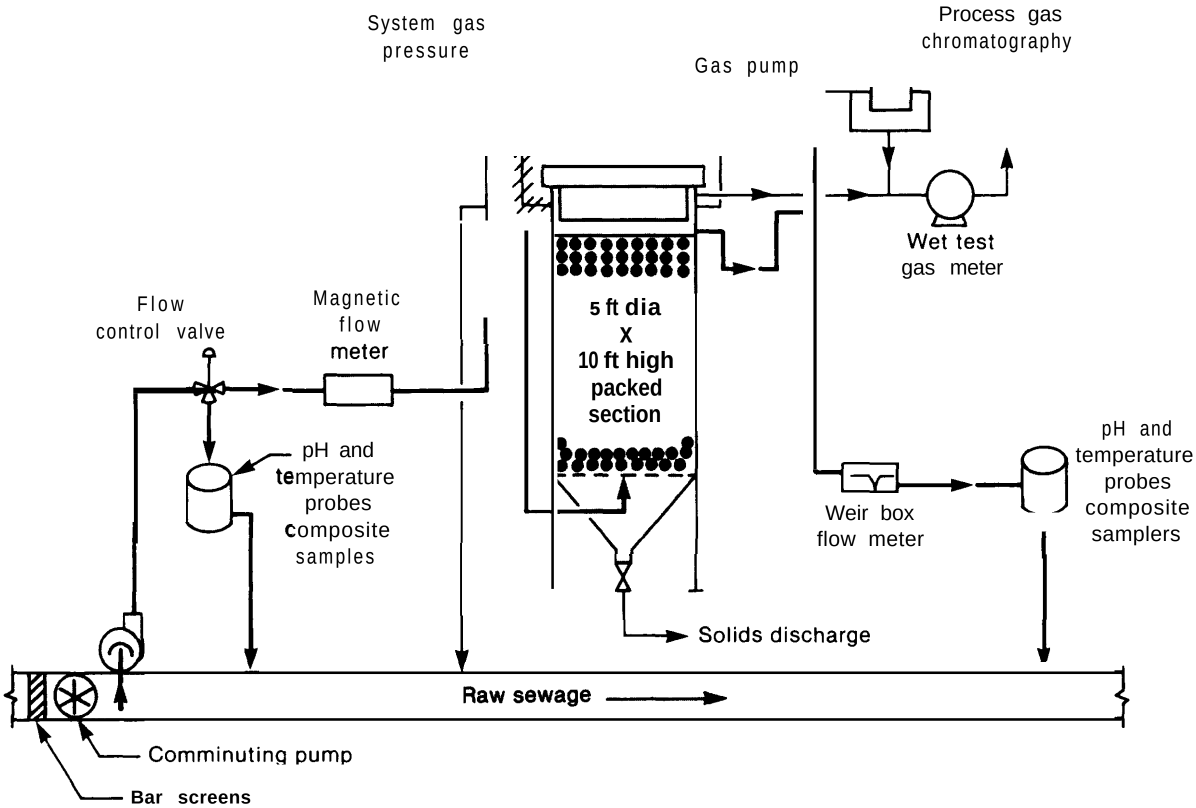
Analyses of bench-scale laboratory results on the AN FLOW system indicate that the system could produce enough energy to make this sewage treatment step energy self-sufficient. [12] As it now exists, however, it is not well suited to energy production.

Like the packed and expanded bed, the mixed-bed systems are intended to provide an inert substance to which the bacteria can attach, thereby preventing them from being flushed out with the effluent. The digester maintains a higher bacteria population. Various designs include netting,[13] strips of plastic, and rough porous digester walls. In all cases, the inert substance increases the resistance to flow and thus the energy needed for pumping increases too, but it decreases the necessary reactor size. Sufficient data are not yet available for a detailed analysis of this tradeoff.

[12] R K Genung and C D Scott, "An Anerobic Bioreactor (AN FLOW) for Wastewater Treatment and Process Applications," briefing presented to the Subcommittee on Energy and Power, House Interstate and Foreign Commerce Committee, Nov 1, 1979

[13] S A Serfling and C Alsten, "An Integrated, Controlled Environment Aquiculture Lagoon Process for Secondary or Advanced Wastewater Treatment," Solar Aqua Systems, Inc, Encinitas, Calif, 1978

Figure 34.—Packed-Bed Digester



SOURCE R K Genung. W W Pitt, Jr , G M Davis, and J H Koon, "Energy Conservation and Scale-Up Studies for a Wastewater Treatment System Based on a Fixed-Film, Anaerobic Bioreactor," presented at 2nd Symposium on Biotechnology in Energy Production, Gatlinburg, Term Oct 2-5, 1979

Expanded Bed

A variation on the packed-bed concept is the expanded-bed reactor (figure 35). In this case the column packing is sand or other very small particles. The feedstock slurry is fed up through the column and the bed of inert material expands to allow the material to pass through. A semifluidized state results, reducing the potential for clogging when relatively concentrated material is fed into the reactor, The process has been found to be quite stable with high organic inputs, short residence times in the digester, and relatively low temperatures (50° to 70° F).[14] The study did indicate, however, that the process would not be a net energy producer due to the energy required to expand the bed.

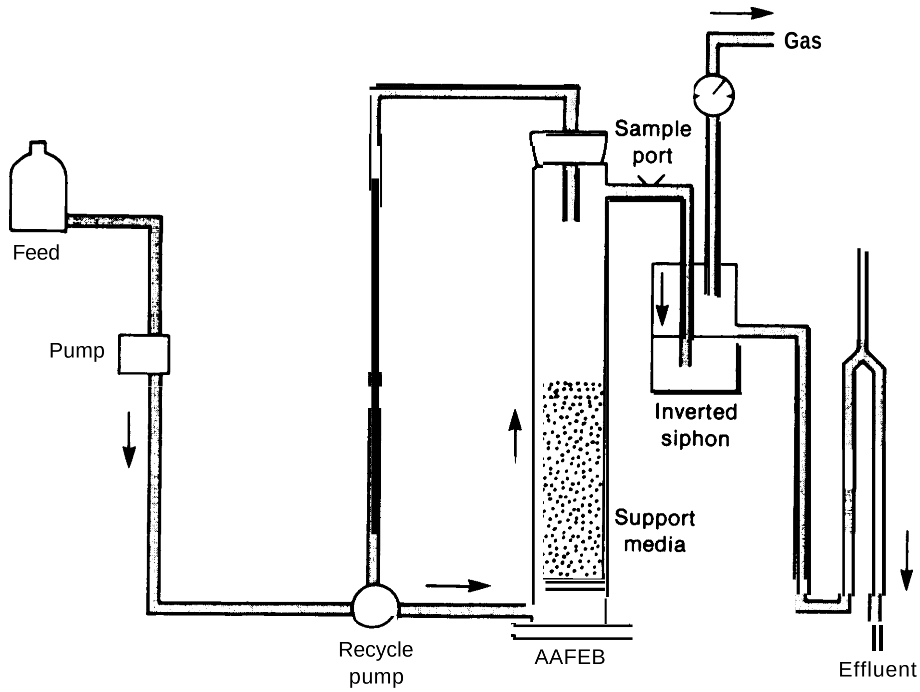
Variable Feed

The idea behind variable feed systems (figure 36) is to store undigested manure in times of low gas demand for use during periods of high demands. The key is to be able to store the manure for long periods (e. g., 6 months) without excessive deterioration. The effect of long-term storage is being investigated,[15] but the systems may be limited to areas with cool summers or to operations in which the gas is used to generate electricity for export during the peak electric demand periods in summer.

[14] M. S. Switzenbaum and W. J. Jewell, "Anaerobic Attached Film Expanded Bed Reactor Treatment of Dilute Organics," presented at *51st Annual Water Pollution Control Federation Conference*, Anaheim, Calif., 1978

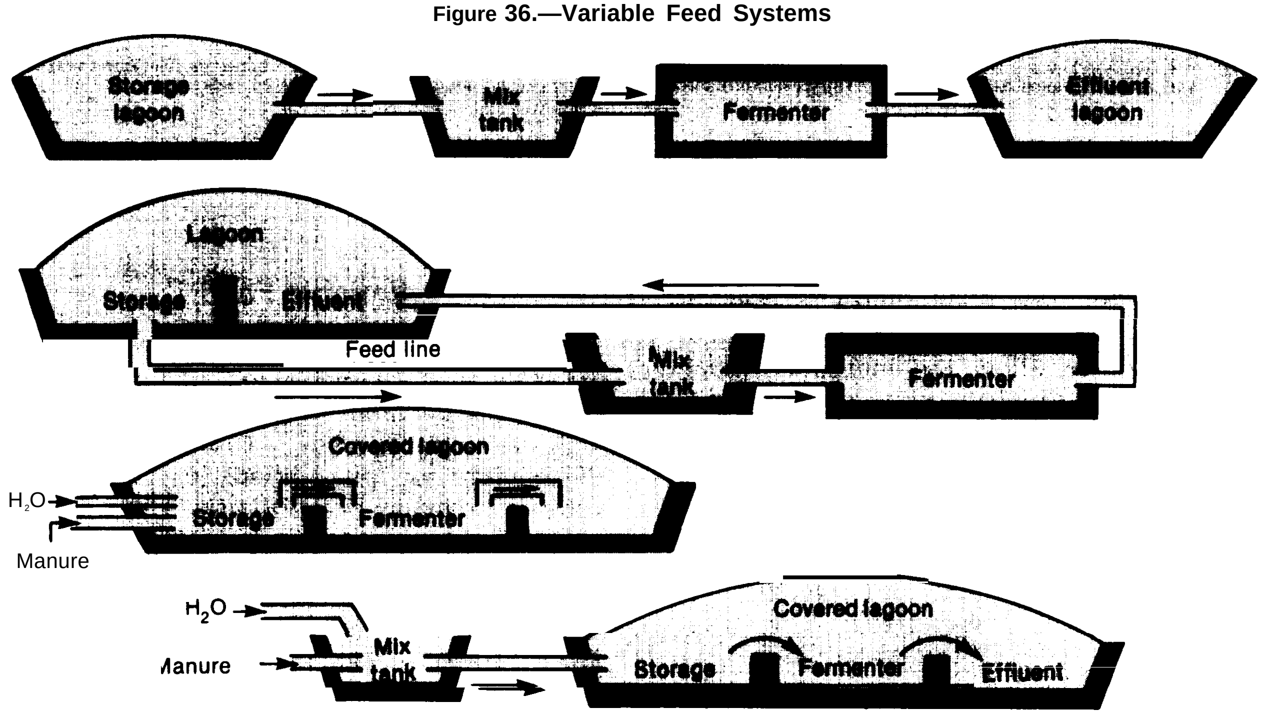
[15] W J Jewell, Cornell University, Ithaca, N Y, private communication, 1978

Figure 35.—Expanded Bed Reactor



SOURCE: M. S., Switzenbaum and W. J. Jewell, "Anaerobic Attached Film Expanded Bed Reactor Treatment of Dilute Organics," presented at 51st Annual Water Pollution Control Federation Conference, Anaheim, Calif., 1978.

Figure 36.—Variable Feed Systems



SOURCE Tom Abeles and David Ellsworth, "Biological Production of Gas, contractor report to OTA by I E Associates, Inc, Minneapolis, Minn 1979

Existing Digester Systems

Fourteen experimental and prototype digesters of animal manure were identified as operational in 1978.[16] **The capacity of these plants varies from less than 1,500 gal to 4 million gal. Two of the prototypes are** owned by individual farmers and are sized for farm use. The 12 others are owned by private firms, universities, or the Federal Government.

Since then, however, the field of anaerobic digestion has been advancing rapidly, and any list of existing operations would be quickly outdated. Several companies currently design and sell digesters and the support equipment. Most systems are currently designed for cattle manure. One example of an apparently successful digester system is on a dairy farm in Pennsylvania. The digester is fed by 700 head of cattle and has been functioning since late fall 1979. The biogas is fed into a dual-fuel diesel engine and supplies about 90 percent of the engine's fuel needs. The engine drives a 125-kW generator (for peak electric demands) and the generator has an average output of 45 kW. The system supplies essentially all of the operation's direct energy needs.

Other systems are operational or are likely to become operational soon. Nevertheless, operating experience is limited and suitable digesters for all types of manures and combined animal operations are currently not available. Consequently, commercialization of the technology could be helped by demonstrating a wide range of digester systems in a variety of confined animal operations so as to provide operating experience and increase the number of operations for which suitable digester systems exist.

[16] D L Klass, **"Energy From Biomass and Wastes,"** in *Symposium on Energy from Biomass and Waste,* Institute of Gas Technology, Washington, D C , Aug 14-18, 1978

Economic Analysis

Aside from the paper and other digestable matter in municipal solid waste (which is not included in this report), the best feedstocks for anaerobic digestion are animal manure, some types of grasses, aquatic plants, and various processing wastes. The supply of aquatic plants is likely to be small in the next 10 years and little information is available on the digester requirements for grasses. Furthermore, with grass at $30/dry ton, the feedstock cost alone would be $4.50/million Btu. More energy at **a lower cost can usually be produced from grass by thermal gasification or combustion.** Hence, animal manure and some processing wastes are the most promising near-term sources of biogas by far. The larger of these two sources is animal manure.

More than 75 percent of the animal manure resource is located on confined animal operations that have less than 800 dairy cows or the equivalent weight of other animals (e. g., 250,000 chickens). Large feedlots account for less than 15 percent of the resource or less than 0.04 Quad/yr (see ch. 5 in pt. **I).** Since it is relatively expensive to transport manure long distances, this economic analysis concentrates on digesters appropriate for onfarm use.

The system analyzed consists of a plug flow digester operating at 700 to 90° F, with a feedstock pond and effluent residue storage pit. (See top schematic, figure 36.) After removal of the hydrogen sulfide (H_2S), the biogas is burned in an internal combustion engine to generate electricity. The electricity is used on the farm (replacing retail electricity) and the excess is sold wholesale to the electric utility. The waste heat from the generator engine is also used onfarm, but any excess heat goes to waste. On the average,15 percent of the energy produced **is** used to heat the **manure entering** the digester and for the other energy needs of the digester (e. g., pumping). (Other systems vary from 10 to 40 percent, depending on the type of digester and the operating conditions.)

There is sufficient gas storage capacity to limit electric generation to those times of the day when the utility or the farmer has peak electric demands; and the feedstock storage allows for seasonal variations in the average daily energy production. Therefore, this system can be used either as a peakload or baseload electric generating system. In a mature system, the electric utility would be able to call for more or less electric generation from onfarm units by sending coded signals along the electric powerlines.

Other systems are possible, including one in which the water in the digester effluent is largely removed (dewatered) and the resultant material sold as a fertilizer or animal feed. Table 58 shows the cost of various systems; the basic digester cost represents the sum of the costs for digester, pumps, pipes, hot water boilers, H_2S scrubber, low-pressure gas compressor, heat exchangers, and housing. The cost of the manure premixing equipment is also included with tanks larger than 40,000 gal. However, these costs should be **viewed** as preliminary and approximate.

Removal of the CO_2 and sales of the gas to natural gas pipelines were assumed not to be feasible in small operations because: 1) the gas pipelines often are not readily accessible, 2) the cost of CO_2 removal equipment is high, and 3) revenues from the gas sales would probably be relatively low. In very large systems, though, production of pipeline quality gas may be feasible.

Table 59 gives the energy that could be produced with onfarm digesters. It also shows the quantities that could be used onfarm and exported for various animal operations in some of the major producing States if farm energy use stays at 1974-75 levels or if it decreases 25 percent **due** to energy conservation. In most cases, the digester energy output is sufficient to meet the energy needs of the livestock operation and in more than half of the cases considered, it also fills the farmer's home energy needs and enables a net export of electricity. With conservation, the situation is even more favorable with respect to energy exports. The lower revenue that the farmer receives for surplus energy as opposed to the replacement of retail energy, however, makes conservation less economically attractive unless the farmer is not energy self-sufficient without conservation. In other words, it is more economically attractive to replace retail electricity than to generate surplus electricity for sales at wholesale rates.

The digester size, capital investment, and operating costs for anaerobic digester-electric generation systems for these various operations are shown in table 60. Assuming the farmers can displace retail electricity costing 50 mill/kWh, sell wholesale electricity for 25 mill/kWh, and displace heating oil used onfarm costing $6/million **Btu, the returns from the digester system are shown in table 61. Also shown are the farmer's** costs for two assumed capital charges: 1) where the annual capital charges are 10.8 percent **01** the investment, i.e.,

Table 58.–investment Cost for Various Anaerobic Digester System Options

	Median capital costs ($1 ,000)				
		Options			
Tank size (gallons)	Basic digester	Dewatering	Electric generator	Feedstock lagoon[b]	Residue pit[c]
10,000	$ 19.6	$34.0	$4.0	$ 6.7	$0.4
20,000	33.7	34.0	5.0	13.4	0.8
40,000	48.1	34.0	6.0	26.9	1.6
80,000	65.6	45.0	12.0	53.7	3.2
200,000	98.8	60.0	45.0	133.0	7,5
400,000	143.6	90.0	70.0	268.3	15.2

[a]Generator is in operation 12 hours each day
[b]Storage for 6 months
[c]Storage for 9 months.

SOURCE Tom Abeles and David Ellsworth, 'Biological Productlon of Gas, " contractor report 10 OTA by I E Associates, Inc, Minneapolis, Mmn , 1979

Table 59.–Anaerobic Digestion: Energy Balance, or the Energy Production Potential and Energy Consumption Potential of Individual Farms in Major Producing States

	Methane energy options			Demands of livestock operation				Household use (1975 levels)		Excess energy (1974 levels)			Excess energy (25% conservation		
	Direct use only	Electricity	Waste heat	1974 levels		25% conserv.				Direct use only	Electricity	Waste heat	Direct use only	Electricity	Waste heat
1974 livestock average number sold	1,000				1,000		1,000		1,000		1,000			1,000	
(inventory)/farm	Btu	10^6 kWh	Btu	10^6 Btu	10^6 kWh	Btu	10^6 kWh	Btu	10^6 kWh	Btu	10^6 kWh	Btu	10^6 Btu	10^6 kWh	Btu 10^6
Turkeys															
Minnesota (124,000). . . . . .,	14,914	877	9,545	8,754	248	6,559	186	326	16	5,835	613	**465**	**8,029**	675	2,660
California (98,000)	11,787	693	7,544	4,714	147	3,536	110	180	16	6,893	530	**2,650**	**8,071**	567	3,828
North Carolina (89,000	10,705	630	6,851	1,931	160	1,448	120	128	22	8,646	448	**4,792**	**9,129**	488	5,275
Broilers															
Minnesota (52,000), ...	522	31	334	357	14	268	11	163	8	2	9	-186	91	12	-97
(198,000).	1,986	117	1,271	1,366	55	1,024	41	163	8	457	54	-258	799	68	84
California (56,000)	562	33	360	350	10	262	8	90	8	122	15	-80	210	17	8
(1,377,000).	13,812	812	8,840	8,606	244	6,454	183	180	16	5,026	552	54	7,178	613	2,206
Arkansas (63,200) ., ., ., . .	634	37	406	314	9	236	7	107	9	213	19	-15	291	21	63
(186,000)	1,866	110	1,194	937	27	703	20	107	9	822	74	150	1.056	81	384
Swine															
Iowa ., ., ..., ...,	325a	19	208	147	28	110	21	155	8	23	-17	-94	60	–10	-57
Missouri . .	325a	19	208	69	22	52	16	136	8	120	-11	3	137	-5	**20**
North Carolina (500) ., ...	325a	19	208	29	13	22	10	64	11	232	-5	115	239	-2	**123**
Dairy cows															
Wisconsin (36) ., ., ..., .,	261	15	167	11	16	8	12	161	8	89	-9	-5	92	-5	-2
New York (71) ., ., .,	521	31	333	25	33	19	25	126	8	370	-10	182	376	-2	188
California (337)	2,459	145	1,574	370	133	278	100	270	24	1,819	-12	934	1,911	21	1,026
Laying hens															
Minnesota (13,000). ., ...,	846	50	541	213	34	160	26	163	8	470	8	165	523	16	218
(41,000)	2,670	157	1,709	672	106	504	80	163	8	1,835	43	874	2,003	69	1,042
Georgia (14,000)	912	54	584	140	34	105	26	72	10	700	10	372	735	18	'407
(41,000)	2,670	157	1,709	410	98	308	74	72	10	2,188	49	1,227	2,290	73	1,329
California (14,000)	912	54	584	224	55	168	41	90	8	598	-9	270	654	5	326
(105,000)	6,838	402	4,376	1,680	414	1,260	310	180	16	4,978	–28	2,516	5,398	76	2,936
Beef(500)	1,527	90	977	–	—	—	—	160	10	1.427	80	817	–	—	—

[a]Includes breeding stock

Assumptions 15% of biogas used to run digester system electric generational 20% efficiency, and 80% of the engine waste heat can be recaptured

SOURCE Tom Abeles and David Ellsworth ``Biological Production of Gas contractor report to OTA by I E Associates Inc, Minneapolis, Minn 1979, *Energy and U/ S Agriculture. 1974 Data Base* (Washington DC Energy Research and Development Administration, 1974)

9-percent interest loan with 20-year amoritization, and 2) where the annual capital charges are 15 percent of the investment.

The principal cost factor in anaerobic digestion is the capital charge, or the cost of the digester itself—thus, favorable financing is the most effective way of reducing the cost to the farmer.

Financing aside, the anaerobic digestion operations that are most economically attractive are relatively large poultry, dairy, beef, or swine operations (enabling an economy of scale) which are also relatively energy intensive (enabling the displacement of relatively large quantities of energy at retail prices) For example, anaerobic digestion on a broiler farm with 198,000 birds in Minnesota is more economically attractive than an equivalent operation with only 52,000 birds (see table 61). On the other hand, the 52,000-bird broiler farm (equivalent to 250 head of cattle in terms of the quantity and quality of manure) is more economically attractive than a 500-head cattle feedlot, because the poultry operation consumes considerably more energy, and thus could better utilize the digester output within its own enterprise.

Based on 1978 fuel prices, the feasibility of anaerobic digestion was assessed for various types of farm animal operations in the various regions of the country. It was found that it would be feasible to digest **so percent of the**

Table 60.–Cost of Various Digesters With Electric Generating Capabilities

1974 livestock average number sold (inventory)/farm	Digester size (1,000 gal)	Capital investment ($1 ,000)	Annual operating costs ($1 ,000)
Turkeys			
Minnesota (124,000).	300	**220**	4.6
California (98,000)	250	**195**	3.9
North Carolina (89,000). .	225	**182**	3.7
Broilers			
Minnesota (52,000)	12	25	**0.9**
(198,000). . . .	45	62	**2.6**
California (56,000)	13	27	**0.9**
(1 ,377,000). . .	300	220	**4.4**
Arkansas (63,200)	14	28	**1.0**
(186,000)	40	59	**2.6**
Swine			
Iowa (500).	10	27	0.8
Missouri (500)	10	27	0.8
North Carolina (500) ... ,	10	27	0.8
Dairy cows			
Wisconsin (32).	10	24	0.6
New York (64)	10	**30**	0.8
California (337).	80	**92**	1.6
Laying hens			
Minnesota (13,000)	34	50	1.6
(41,000)	100	103	1.7
Georgia (14,000)	34	50	1.6
(41,000)	100	103	1.7
California (14,000)	35	51	1.6
(105,000)	250	169	3.0
Beef(500)..	20	43	0.7

SOURCE SOURCE Tom Abeles and David Ellsworth, "Biological Production of Gas," contractor report to OTA by I. E Associates, Inc ,Minneapolis, Minn. ,1979

animal manure to produce electricity and onsite heat if the effective annual capital charges were 6.6 percent of the investment. (Digestion was deemed feasible if the returns from displacing onsite energy use and wholesaling excess electricity were greater than the capital and operating costs for the anaerobic digestion energy system.) This effective capital charge could be achieved by a 9-percent interest, 20-year loan with 4.2-percent annual tax writeoff. Other possible credits could be available through combinations of Agricultural Stabilization and Conservation Service pollution abatement cost sharing, soil conservation district cost sharing, energy credits, and other incentives, although these are not included in the feasibility calculations. **In table 62, the percent of the manure resource that would be feasible** for energy production with the 6.6-percent capital charge is shown for various manure types and regions. Also shown

Table 61 .–Annual Costsand Returns From Digester Energy Only

1974 livestock (inventory)/farm	Return from energy displacement and sales of electricity ($1,000)	Digester costs (operating + capital) ($1,000): 10.8% annual capital charge	Digester costs (operating + capital) ($1,000): 15% annual capital charge
Turkeys			
Minnesota (124,000). . . .	81	28	38
California (98,000)	51	25	33
North Carolina (89,000)..	36	12	31
Broilers			
Minnesota (52,000)	3,3	3.6	4.7
(198,000) . . .	12	9.3	12
California (56,000)	3.4	3.8	5.0
(1,377,000). . .	80	28	37
Arkansas (63,200)	3.8	4.0	5.2
(186,000)	9.9	9.0	11
Swine			
Iowa (500).	2.2	3.7	4.9
Missouri (500)	2.2	3.7	4.9
North Carolina (500)	1.5	3.7	4,9
Dairy cows			
Wisconsin	1.8	3.2	4.2
NewYork (64)	2.5	4.0	5.3
California (337)	11	12	15
Laying hens			
Minnesota (13,000)	4.6	7	9.1
(41,000)	12	13	17
Georgia (14,000)	3.7	7.	9.1
(41,000)	9.5	13	17
California (14,000)	4.6	7.1	9.3
(105,000)	31	21	28
600/(500)	3.2	5.3	7.2

SOURCE SOURCE Tom Abeles and David Ellsworth, "Biological Production of Gas, " contractor report to OTA by I E Associates, Inc. , Minneapolis, Minn., 1979.

are the quantities of manure that would be feasible if the digester effluent were dewatered and sold as a fertilizer at $1 O/dry ton over the revenues available from sales of the raw manure as a fertilizer. Furthermore, if the dewatered effluent could be sold for feed, higher credits may be possible based on the protein content of the effluent.[17] Although the feasibility of these higher credits is unproven as yet, the selling of digester effluent as feed or fertilizer would substantially expand the quantity of manure that could be digested economically.

Turkey farms tend to be the most economic because of their rather large average size and

[17] Biogas **of Colorado, "Energy Potential Through** Bioconver**sion of Agricultural Wastes, "** *Phase //, Final Report to the Four Corners Regional Commission,* **demonstration** project **FCRC No 672-366,002, Arvada,** Colo **, 1977**

Table 62.–Economic Feasibility of Anaerobic Digestion (percent of total manure resource that can be utilized economically[a])

Region	Total usable manure problem	Layers	Broilers	Turkeys	Cattle on feed	Dairy	Swine
Northeast	52%	68%	82%	98%	6%	43%	—
Southeast	65	54	75	90	45	80	—
Appalachia	47	51	85	89	8	26	—
Corn Belt	17	38	67	89	9	19	8%
Lake States	30	50	90	98	6	23	8
North Plains	39	37	46	96	55	12	—
Delta	69	68	82	86	21	37	—
South Plains	82	76	87	94	90	49	—
Mountain	75	82	44	95	83	49	—
Pacific	88	78	97	98	90	89	—
Alaska	69	0	0	0	0	82	—
Hawaii	70	35	82	0	89	99	—
National totals	49 + 20[b]	59	81	94	61	41	5
With fertilizer enhancement assumption of $10/dry ton	69 + 30[b]	85	95	99	72	60	35

[a]Assuming feedstock lagoon (6-month storage), residue pit (9-month storage), generation of heat and electricity for onsite use and electricity for wholesale sales, and an annual capital charge of 6.6% of the Investment Also assumes 1978 energy costs as follows home healing $3 80/million Btu; farming heat $5 40/million Btu; retail electricity according to DOE, *Typical Electric Bills, January 1978*, October 1978, and wholesale elecrricity 25 mill/kWh

[b]Estimated uncertainty These correspond to weighted average percentages

SOURCE Tom Abeles and David Ellsworth, 'Biological Production of Gas, " contractor report to OTA by I E Associates, Inc, Minneapolis, Minn, 1979

the relatively large amount of thermal energy consumed by them. Swine operations, however, are usually too small to be economically attractive, for the energy alone, but because of odor problems these may also be attractive.

If 50 percent of the animal manure on confined animal operations in the United States is converted to electricity and heat, about 7 billion kWh of electricity per year (equivalent to about 1,200 MW of electric generating capacity) and about 0.08 Quad/yr of heat would be produced by 0.12 Quad/yr of biogas. At 70-percent utilization, electricity equivalent to about 1,600 MW of electric generating capacity would be produced along with 0.11 Quad/yr of heat.

In either case some of the heat would be wasted in the systems described above. There is, however, the possibility of expanding the operation to use the excess heat, for example, by building greenhouses. This could improve the economics, but it would require major adjustments in the farmer's operation. In the end, site-specific economics and the inclination of the individual farmer will determine whether such options are adopted.

Care should be exercised when using these data. They are based on a number of approximations and they cannot be taken too literally. They do, though, indicate the general trends as to economic feasibility and they show that a substantial quantity of the manure produced on livestock operations could be used economically to produce energy, if the effective capital charges are reduced through various economic incentives.

Environmental Impacts of Biogas Production: Anaerobic Digestion of Manure

Anaerobic digestion of feedlot manure is considered to be an environmentally beneficial technology because it is an adaptation of a pollution control process. The energy product–biogas–is basically a byproduct of the control process, which converts the raw manure (which often represents a substantial disposal problem) into a more benign sludge waste. Where the manure was used as a fertilizer and soil amendment, the digestion wastes can substitute for the manure while eliminating some of its drawbacks.

The environmental benefits associated with reducing feedlot pollution are extremely important. The runoff from cattle feedlots is a source of high concentrations of bacteria, suspended and dissolved solids, and chemical and biological oxygen demand (COD/BOD). This type of runoff has been associated with: large and extensive fish kills because of oxygen depletion of receiving waters; high nitrogen concentrations in ground and surface waters, which can contribute to the aging of streams and to nitrate poisoning of infants and livestock; transmission of infectious disease organisms (including salmonella, *leptospirosis,* and *coliform* and *enterococci* **bacteria) to man, livestock, and wildlife; and coloring of streams.**[8] **Other problems associated with feedlots include attraction of flies and obnoxious odors.**

Because anaerobic digestion is a relatively simple process not requiring extreme operating conditions or exotic controls, biogas facilities may be designed for very small (10 cow) operations as well as large feedlots. The environmental impacts will vary accordingly. For example, recycling of wastewater may be possible for the larger operations; it is not likely to be possible for the small onfarm digesters because of high water treatment costs. The product gas from the smaller units is likely to be used onsite and, depending on its use, may or may not be scrubbed of its HIS and ammonia (N H,) content; the product from very large units may be upgraded to pipeline quality by removing these pollutants as well as the 30 to 40 percent of the CO, fraction in the biogas.

The major problem associated with the digestion process is waste disposal and the associated water pollution impacts that could result. As noted above, anaerobic digestion is basically a waste treatment technology, but although it reduces the organic pollution content of manure it does not eliminate it. The combination of liquid and solid effluent from the digester contains organic solids, fairly high concentrations of inorganic salts, some concentrations of H_2S and NH_3, and variable amounts of potentially toxic metals such as boron, copper, and iron. For feed lot operations where the manure is collected only intermittently, small concentrations of pesticides used for fly control may be contained in the manure and passed through to the waste stream.

A variety of disposal options for the liquid and sludge wastes exist. Generally, wastes will be ponded to allow settling to **occur. The liquid, which is high in organic content, can be pumped into tank trucks (or,** for very large operations, piped directly to fields) to be used for irrigation and fertilization. The high salt content and the small concentrations of metals in the fluid make it necessary to rotate land used for this type of disposal. Large operations may conceivably treat the water and recycle it, but treatment cost may prove to be prohibitive. Other disposal methods include evaporation (in arid climates), discharge into waterways (although larger operations are likely to be subject to zero discharge requirements by the Environmental Protection Agency), and discharge into public sewage treatment plants. In all cases, infiltration of wastewater into the ground water system is a possibility where soils are porous and unable to purify the effluent through natural processes. As with virtually all disposal problems of this nature, this is a design and enforcement problem rather than a technological one; if necessary, ponds can be lined with clay or other substances for ground water protection.

The organic content of the effluent, which varies according to the efficiency of the digester, will represent a BOD problem if allowed to enter surface waters that cannot dilute the effluent sufficiently. Similar problems can occur with organics leached from manure storage piles. However, this problem exists in more severe form in the original feedlot operation.

The sludge product can be disposed of in a landfill, but it appears that the sludge has

[8] *Environmental Implications of Trends in Agriculture and Silviculture, Volume II:* **En** *vironmental Effects* **of** *Trends* (Washington, **D C Environmental Protection Agency,** December **1978), E PA-600/ 1-78-102**

[9] *Solar Program Assessment Environmental factors, Fuels From Biomass* **(Washington, D C Energy Research** and **Development** Administration, **March 1977), ERDA** 77-47/7

value either as a fertilizer or cattle feed if the heavy metals content is not too great. Successful experience with anaerobically digested municipal sludges, which clearly have higher concentrations of heavy metals, indicates that use of the feedlot-derived sludge as fertilizer should present no metals problem.[20] In numerous applications overseas, the sludge is considered a substantial improvement over the previously used manure fertilizer. In areas where chemical fertilizers are not available or are too expensive, the retention of the manure's fertilizer value is a particularly critical benefit of the biogas process.

Although the H_2S (and related compounds) content of the effluent may present some odor problems, this problem, as well as that of the very small pesticide content, should be negligible.[21]

The gas produced by the digester will contain small (less than 1-percent each)[22] concentrations of H_2S and NH_3. If the gas is burned onsite without scrubbing out these pollutants, combustion will oxidize these contaminants to sulfur and nitrogen oxides. Because the H_2S will form mostly sulfurous and sulfuric acids, which are extremely corrosive to metal, the biogas has limited use if it is not scrubbed. For example, scrubbing is a requirement if the gas is to be used in an internal combustion engine. Simple and inexpensive scrubbing methods are available, using an "iron sponge" of ferric oxide and wood shavings to react the gas with the iron to form ferric sulfide.[23] However, even if the gas were not scrubbed, the pollutant concentrations caused by biogas combustion should be of little consequence to public health as long as the combustion did not take place in a confined area. For example, combustion of biogas produced from fresh cow manure might generate sulfur oxides on the order of 0.1 lb/million Btu,[24] compared to the Federal requirement of 1.2 lb/million Btu for coal combustion in large utility boilers.

The major air pollution problem of anaerobic digestion, therefore, is not from combustion of the product gas, but from leaks of raw gas from the system. For a manure sulfur content of 0.2 percent and digester pH of 7.2, the raw biogas can contain H_2S in concentrations of nearly 2,000 parts per million (ppm).[25] Although exposure to this full concentration seems extremely unlikely, concentrations of 500 ppm can lead to unconsciousness and death within 30 minutes to 1 hour, and concentrations of 100 ppm to respiratory problems of gradually increasing severity over the course of a few hours; the Occupational Safety and Health Administration's standard is a maximum permissible exposure level of 20 ppm.[26]

Because of rapid diffusion of the gas, health problems associated with H_2S exposures are likely to be confined to these occupational exposures. However, venting of raw gas can cause severe odor problems to the general public. In this case, odor problems associated with gas venting should be compared to the similar (but more certain) odor problems associated with the sometimes haphazard treatment of manure that the biogas operation replaces.

Because methane is explosive when mixed with air, strong precautions must be taken to avoid biogas leakage into confined areas and to prevent any possibility of the gas coming into contact with sparks or flames. Although this will be a universal problem with biogas facilities, it is particularly worrisome if small units proliferate.

If normal operating conditions hold biogas leakage to near-zero levels, the powerful odor of the H_2S contaminant would serve as an early warning of a leak. Because low concentrations of H_2S will deactivate the sense of smell, the acceptance of small leaks as "stand-

[20] *Methane Generation From Human, Animal, and Agricultural Wastes* (Washington, D.C.: National Research Council, National Academy of Sciences, 1977), Library of Congress catalog No. 77-92794.

[21] M. C. T. Kuo and J. L. Jones, "Environmental and Energy Output Analysis for the Conversion of Agricultural Residues to Methane," *Symposium on Energy From Biomass and Waste*, Institute of Gas Technology, Washington, D.C., Aug. 14-18, 1978.

[22] *Solar Program Assessment*, op. cit.

[23] Kuo and Jones, op. cit.

[24] Ibid.

[25] *Solar Program Assessment*, op. cit.

[26] Ibid.

ard operating practice" would eliminate this safety factor.

The institutional problems associated with assuring that there is adequate control of digester impacts are very similar to those of ethanol plants: there is an attraction towards smaller size ("on farm") plants which may have some advantages (mainly ease of locating sites for waste disposal and smaller scale local impacts) but which cannot afford sophisticated waste treatment, are unlikely to be closely monitored, and may be operated and maintained by untrained (and/or part-time) personnel. Some of the potential safety and health problems probably will respond to improved system designs if small onfarm systems become popular and the size of the market justifies increased design efforts on the part of the manufacturers. The ease of building homemade systems, however, coupled with farmers' traditional independence should provide potent competition to the sale of manufactured (and presumably safer) systems.

Research, Development, and Demonstration Needs

Below, the more important research, development, and demonstration needs for anaerobic digestion are divided into the general areas of microbiology, engineering, and agriculture.

Microbiology

The whole range of studies related to how anaerobic digestion works should be addressed. This includes identifying the bacteria and enzymes involved, studying the bacteria's nutrient requirements (including trace elements), identifying optimum conditions for the various conversion stages, and investigating why some feedstocks are superior to others. Much of this is in the realm of basic research needed to understand the processes involved so that the yields, rates, control, and flexibility of anaerobic digestion can be improved.

Engineering

A large number of different digester types need to be demonstrated to aid in optimizing the safety and reliability of digester systems while reducing the cost for onfarm use or for large-scale systems. The unique problems and opportunities of various types of animal operations should also be addressed by the various digester systems. There are also numerous design alternatives that could lower the digester costs, and these should be thoroughly examined.

Electric power generation and the related feedstock pumping is a weak area in digester systems, particularly with respect to reliability, maintenance, and efficiency of the engine-generator units. Development work for small engines intended to use biogas and the related pumps could lead to improvements in these areas, and fuel cells capable of using biogas should be developed. Development work is also needed into the best ways the farm generator can supply the electric utility grid during periods of high demand without undue inconvenience for the livestock operation.

Agriculture

More needs to be known about the difference between digested and undigested manure. The digested manure should be investigated in order to determine its value as a fertilizer, animal feed, and nutrient source for aquatic plants. High-value uses for the digester effluent, proved through thorough testing, could significantly improve the economics of anaerobic digestion.